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Digital twin-based alternate ego modeling and simulation: Eva Herzigová as a 3D MetaHuman avatar

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ABSTRACT

Due to Dimension Studios and Unsigned Group, by likeness and movement digitization, the human supermodel Eva Herzigová's highly realistic metahuman and 3D digital twin lead to perpetual career extension (e.g., on virtual runway shows by catwalk replication or in advertising campaigns by particular pose adoption), including in virtual worlds such as metaverse spaces, by use of extended reality technologies, in terms of virtual clothing, digital hair, skin texture, facial and body expressions, and makeup styling as avatar appearance and persona. In this paper, we show how, by likeness capturing (e.g., signature walk by motion capture shoot for face and body movement tracking) and virtual clothing, Eva Herzigová's hyperreal 3D avatar (lifelike 3D digital human clone or realistic virtual human) is configured with subsequent restyled hair and make-up, 3D clothing modeling, and extended reality fashion shows on virtual catwalks or campaign shoots. We clarify that photographic reference materials and a sensor-based motion capture suit assisted Metahuman Creator in capturing facial and motion data for Eva Herzigová's digital avatar, configuring realistic depiction and virtual activations of beauty standards, in addition to digital likeness, signature style, talent representation, and narrations, typifying digital human creation and presence in virtual worlds (e.g., for metaverse-based shoots). We conclude that Eva Herzigová's hyperrealistic 3D digital human twin and MetaHuman avatar operate as a styled virtual alter ego and versatile personal brand extension by motion capture technologies for immersive virtual fashion shows, live video streams and broadcast, and digital wearable modeling.

KEY WORDS
Eva Herzigová, digital twin, hyperrealistic 3D digital human twin, MetaHuman avatar appearance and persona, motion capture technologies, artificial intelligence, AI

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Introduction

3D image generation and motion segmentation algorithms, image-based 3D reconstruction and data acquisition technologies, and physio- and neuro-behavioral sensors can be deployed in 3D facial expression synthesis, perceptual and cognitive performance, expressive body language and movements, emotional and personality features, and interactive social behaviors. Sensor network clustering and data augmentation algorithms, 3D clothing simulation and virtual try-on technologies, and Internet of

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Things (IoT)-based machine vision and image sensor devices can be leveraged in multi-sensory object localization, recognition, and representation, realistic 3D avatar facial appearance animation, and photo-realistic synthetic image and scene-aware 3D human avatar pose generation. Mediated virtual self-expression and representation, avatar-mediated self-disclosures and social identification, and facial movement detection and recognition develop on multi-modal image-based 3D object detection and scene perception algorithms, IoT-connected wearable and spatial computing devices, and human-like tactile sensing and perception technologies.

Due to Dimension Studios and Unsigned Group, by likeness and movement digitization, the human supermodel Eva Herzigová's highly realistic metahuman and 3D digital twin lead to perpetual career extension (e.g., on virtual runway shows by catwalk replication or in advertising campaigns by particular pose adoption), including in virtual worlds such as metaverse spaces, by use of extended reality technologies, in terms of virtual clothing, digital hair, skin texture, facial and body expressions, and makeup styling as avatar appearance and persona.

Real-time model volumetric scanning, augmented reality try-on technologies and filters, and 3D real-time design can be harnessed in performance capturing and hologram streaming for alternate egos and personal brand extension as digital personalities and virtual counterparts by accurate lifelike features and authentic expression, without body and face-enhancing alterations (e.g., skin smoothing, eye widening, lip plumping, or lash darkening).

1. Literature review

3D spatial computing and metaverse technologies, facial shape and appearance modeling, and spatial mapping algorithms (Al-Emran & Deveci, 2024; Grupac & Lăzăroiu, 2022) enhance lifestyle behavior actions and habits of 3D photorealistic avatars across engaging extended reality environments. 3D garment simulation technologies improve multi-dimensional metaverse experiences, behaviors, and preferences throughout avatar motion and virtual scene control, image-based 3D scene representation, and 3D clothed avatar and facial appearance reconstruction.

Animatable 3D virtual human avatar tools (Bugaj et al., 2023; Zhang et al., 2023a) shape 3D-aware virtual clothed human generation, reconstruction, and animation, image-based autonomous virtual 3D object recognition, segmentation, classification, and modeling, and generative 3D-aware human face and image synthesis. 3D-aware human facial appearance and expression analysis, 3D scene representation technologies, and animatable neural human avatar generative modeling optimize controllable 3D-aware human avatar generation and image synthesis, reconstruction, and animation, single image-3D pose mapping and estimation, and 3D human representation decomposition. Animatable 3D-aware clothed human generation and modeling enhance photo-realistic human image, pose, and shape synthesis, virtual body appearance variations, and 3D neural object and scene representation.

Deep learning visual and speech recognition algorithms (Zhang et al., 2023b; Zvarikova et al., 2023) configure contextual deep convolutional neural network-based facial feature and body shape virtualization, single image-based 3D human clothed avatar reconstruction and pose estimation, and 3D human body texture, shape, and pose estimation, tracking, and prediction. Visual image and geospatial mapping algorithms articulate skin texture reconstruction, simulation data reconstructed appearance, and 3D garment texture visualization. Perceptual image algorithms and 3D avatar motion capture technologies assist in 3D human pose and physics-based appearance estimation, garment and hairstyle simulation, and human body avatar modeling.

Computer graphics and affective haptics technologies, multimodal visual interaction and voice recognition tools, and computer animation and speech synthesis techniques (Cui & Liu, 2023; Valaskova et al., 2022) assist in motion capture animation, personalized voice expression and visual appeal, and realistic texturing and lighting. Natural speech recognition and voice generation technologies enable digital human image construction in terms of hyper-realistic anthropomorphic appearance, facial expression and emotion recognition, and real-time interactive feedback capabilities. Image and voice recognition technologies, synthetic data augmentation, and social simulation emotion modeling further realistic facial image reconstruction, physiological and behavior data sharing and interoperability, and object visual and body shape appearance. Hyper-realistic immersive experiences can be attained by use of motion pose capture and automatic speech recognition technologies, image-based temporally coherent visual and spatial semantic representation, and visual perception and semantic object recognition algorithms.

Physics-based clothing animation and simulation, full-body motion capture analysis, and animatable full-body appearance modeling (Kliestik & Lăzăroiu, 2023; Xiang et al., 2022) configure pose-driven full-body avatars, neural rendering-based physically-simulated garments and photorealistic clothing, and full-body avatar representation and movement predictions. Photorealistic neural clothing appearance modeling and 3D human body pose and shape reconstruction and estimation articulate emotionally expressive animatable photorealistic full-body avatars, elaborate body‒clothing interactions, and virtual garment resizing. 3D human avatar and realistic clothing modeling and physically-realistic clothing simulation assist in photorealistic avatar garments and clothing appearance, avatar self-expression, and photorealistic synthetic human representation and clothing animation.

2. Methodology

Realistic avatar and remote sensing technologies, deep learning-based visual reasoning and sentiment analysis, and behavioral pattern and sensor data context-aware interpretation enable 3D face reconstruction and modeling, deep learning-based semantic segmentation, and body shape and emotional avatar perception across 3D virtual simulation environments. Speech visualization and tactile sensor technologies articulate 3D garment and visual object appearance modeling, complex adaptive IoT network dynamical behavior simulation, and multisensor data fusion and integration. Visual recognition and multilayer perceptron algorithms assist in head, hand, eyebrow, eye, and lip movement tracking and synchronized capture, visual motion awareness, and 3D spatial object modeling across visually-consistent photo-realistic virtual environments.

Computer vision and graphics techniques, social interaction and environment data, and sensing and perception systems further dynamic deep generative and neural scene modeling, visual data processing, and semantic scene understanding. Semantic reasoning and multi-view imaging techniques, lifestyle behavior and body shape modeling, and deep fusion convolutional neural networks shape animatable 3D clothed human and 4D dynamic scene reconstruction across 3D spatial data analytics and infrastructures. Semantic ontology and multimodal sensing technologies, visual language navigation and semiotics, and human digital twin body and behavior modeling optimize image visual coherence, mood and emotion recognition, and body shapes and sizes. Space mapping and visual perception algorithms, visual object appearance modeling, and 3D facial expression and motion tracking enhance physical condition detection and monitoring and remote sensing image scene classification, processing, and fusion by use of synthetic motion and perception data. 3D human body and image appearance modeling improves remote sensing image classification, physical world attributes and states, and multiscale knowledge mining.

Photographic reference materials and a sensor-based motion capture suit assisted Metahuman Creator in capturing facial and motion data for Eva Herzigová's digital avatar, configuring realistic depiction and virtual activations of beauty standards, in addition to digital likeness, signature style, talent representation, and narrations, typifying digital human creation and presence in virtual worlds (e.g., for metaverse-based shoots). Our analysis covers reality capture, mocap shoot, Z Brush, clothing simulation, hair creation, make up, skin and clothing texture, unreal animation, environment build, and lighting pass.

3. Results

3D cloth modeling and simulation (Valaskova et al., 2022; Xiang et al., 2022) enable multi-view clothing capture, photorealistic texture-based clothed body shape estimation, and physically-simulated 3D contextual detail-aware interactive virtual clothing animation by use of reality capture technologies. 3D virtual fabric simulation, silhouette image analysis, and structure-preserving 3D and context-aware virtual garment modeling further physically-inspired clothing appearance, photorealistic clothing texture, and 3D human skeleton motion prediction, recognition, capture, generation, analysis, tracking, segmentation, and representation with regard to photorealistic animatable clothed avatars. Photorealistic clothing and body motion animation, personalized photorealistic avatar generation and representation, and photorealistic texture and clothing appearance generation can be attained by generative artificial intelligence (AI) synthetic and kinematic

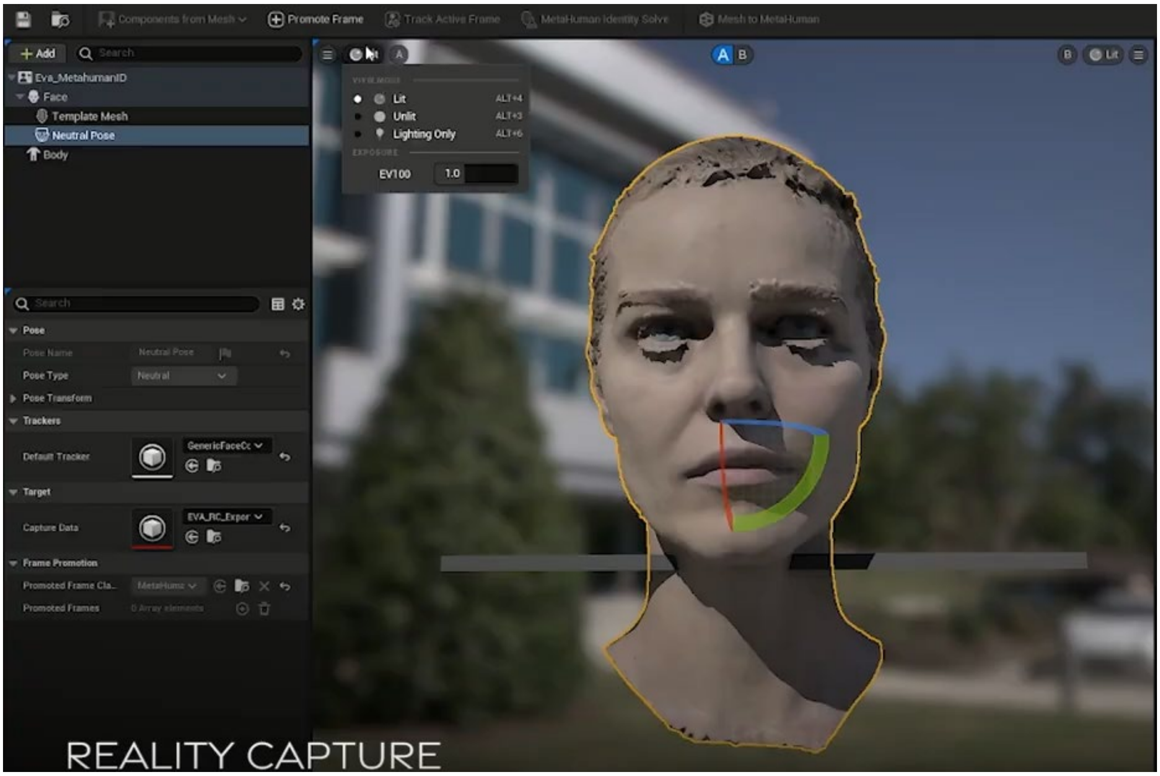

Fig. 1. Reality capture
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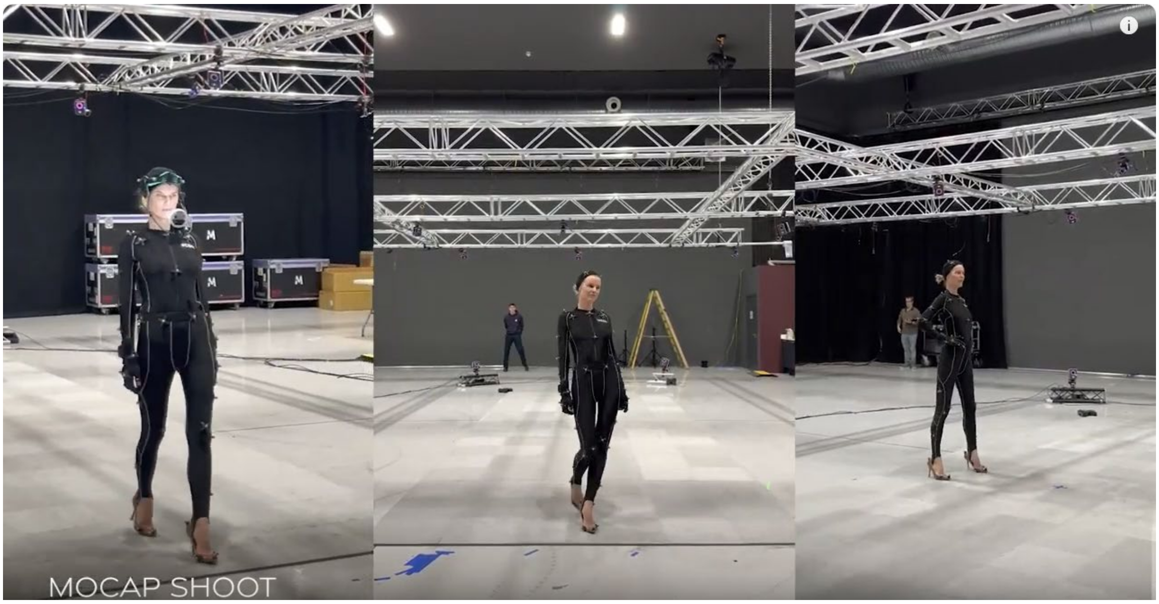

Fig. 2. Mocap shoot
Source: © Dimension Studio and Unsigned Group.

body pose data, dynamic gesture, multi-modal emotion, and skeleton-based action recognition algorithms, and 3D garment and photorealistic appearance modeling.

Neural 3D clothed-human body reconstruction, 3D realistic skin and hair modeling, and autonomous simulated virtual agent intentionality (Bugaj et al., 2023; Wang et al., 2024) can be achieved by 3D motion data processing and analysis, sensor-based 3D semantic mapping, and syntactic navigation and facial expression data with regard to digital human appearance and photo-realistic 3D clothed virtual humans. Cognitive mapping algorithms, real-time subtle facial expression capture, and 3D human shape representation and modeling shape photo-realistic 3D human and synthetic clothing reconstruction in 3D immersive visualization environments. Digital twin mapping and immersive technologies, synthetic human data, and 3D motion capture systems optimize 3D facial expression and skin texture modeling and 3D machine learning-based simulation in immersive virtual reality simulation environments (Figure 1).

Visual sensor and motion detection data, 3D digital twin visualization technologies, and activity-tracking algorithms (Grupac & Lăzăroiu, 2022; Jiang et al., 2024) improve intelligent wearable garment, deep learning 3D limb movement and vision sensor-based human tracking, and human pose estimation with regard to mocap shoots. Image sensor and gesture recognition technologies, deep learning sensor fusion and neuromorphic computing algorithms, and intelligent 3D garment and emotion recognition systems can be harnessed in 3D skeletal rendering, deep learning network-based facial expression recognition, and 3D hand and leg tracking. Visual imaging technologies, garment sensor networks, physiological and motion data, and wearable textile sensors can be deployed in wearable sensor clothing, 3D sensor data mapping and virtual scene generation, spatial movement patterns, human body movement reconstruction, and facial feature detection. Machine learning and computer vision algorithms and space syntax simulation (Chen et al., 2021; Valaskova et al., 2022) enable convolutional neural network-based facial expression, hand gesture, and body shape, and action recognition modeling, photorealistic deep neural network and sensory data-based 3D digital human reconstruction, and image-based 3D object reconstruction and scene representation. 3D visualization and full body motion capture systems and 3D generative AI simulation technologies further generative AI digital twin-based virtual reality simulation and socio-spatial modeling by sensor-based physiological data and unstructured image collection, image representation reconstruction, and 3D semantic occupancy and navigational pattern predictions in relation to mocap shoots. Networked social-emotional interactivity, sensor-based situational awareness, deep learning-based 3D human representation, complex immersive spatial and social dynamics simulation, and photorealistic image generation and texture rendering can be attained by virtual 3D and computer-based visual simulation technologies (Figure 2).

Human–machine interaction and sensor network technologies (Fjørtoft Ystgaard et al., 2023; Zvarikova et al., 2023) can be leveraged in immersive augmented reality visualization, social emotion, behavior, intention, and attitude mapping, and contextual environment understanding in relation to human digital twins across human-centric IoT network infrastructures by use of Z Brush. Embodied interaction modalities, interconnected quantified selves, design process participatory involvement, collaborative task performance assessment, algorithmic social behavior, and meaningful human-like features develop on sensors and actuators, algorithmic modeling and semantic mapping techniques, shared knowledge and action mechanisms, and face recognition and wireless sensor network technologies with regard to artificial social peers across pervasive IoT environments. Immersive extended reality technologies, photorealistic avatar modeling, and perceptual image processing and spatial cognition algorithms (Alldieck et al., 2022; Grupac & Lăzăroiu, 2022) enhance deep neural network-based photorealistic 3D human visualization and reconstruction by object–scene semantics, immersive virtual apparel try-on, 3D virtual clothing, and realistic 3D avatar animation. Photorealistic digital human modeling and immersive 3D human body shape and pose reconstruction improve emotionally expressive dressed 3D avatars in terms of predicted appearance and skin tone perceptual quality, virtual garment rendering, and visual motion perception by use of Z Brush. Deep learning-based semantic segmentation, 3D scene capturing and object reasoning techniques, 3D facial appearance modeling, and multiscale shape representation and analysis can be harnessed in 3D scene and clothed human reconstruction and human-like avatar representation (Figure 3).

Physical appearance, facial expression, body shape and movements, voice recognition, and social personality, together with emotional and physiological state, body movement, and natural speech replication, with regard to multiple fusion technology-based virtual human individuals (Cui & Liu, 2023; Kliestik et al., 2022), integrate 3D deep learning data-driven reconstruction and scanning techniques. Human appearance and communication, emotion recognition and expression, facial and body movement, and interaction behavior simulation require emotion capture and recognition technologies, convolutional neural network and visual perception algorithms, sensor-based gesture capture and eye-tracking devices, emotional speech synthesis systems, and environmental behavior monitoring sensors. Natural language processing and speech synthesis necessitate

Fig. 3. Z Brush
Source: © Dimension Studio and Unsigned Group.

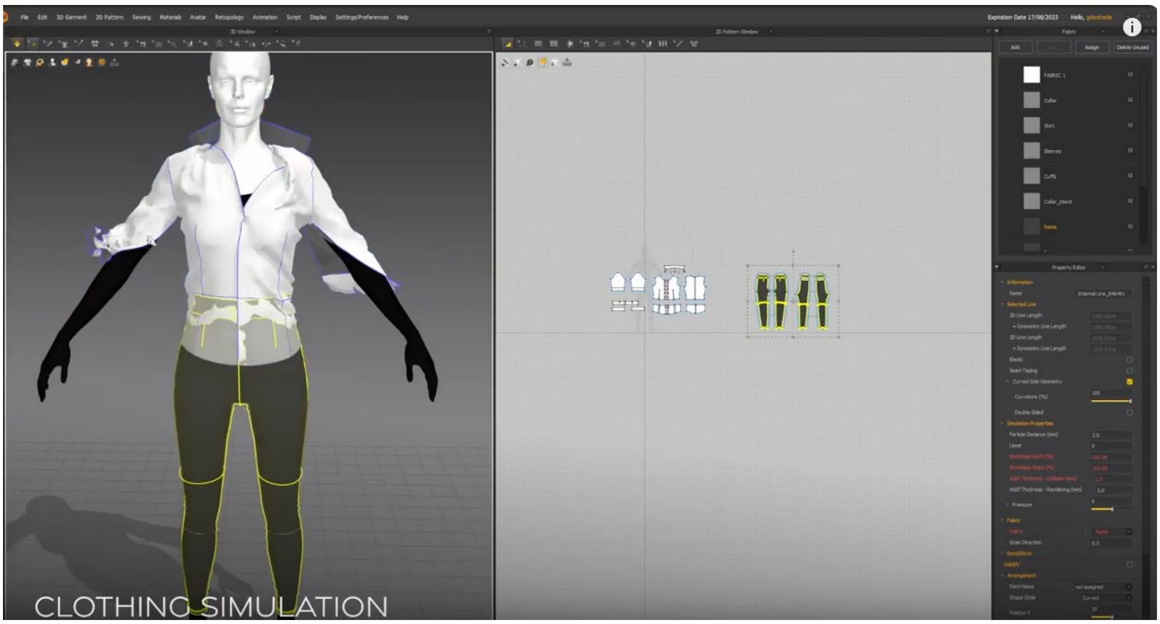

Fig. 4. Clothing simulation
Source: © Dimension Studio and Unsigned Group.

deep learning-based face image mapping and digital human appearance and emotional expression simulation for 3D modeling technology-based digital humans. Computerized facial animation and motion control technologies, deep and machine learning algorithms, and image-based 3D reconstructed scene segmentation are pivotal in multimodal human interaction behavior simulation and modeling in immersive augmented reality and anthropomorphic simulation environments. Convolutional neural network deep learning 3D pose estimation and body shape visualization technologies (Correia & Brito, 2023; Zvarikova et al., 2023) can be deployed in computer vision-based 3D human body reconstruction, 3D human silhouette and skeleton modeling, and realistic 3D body and object representation. 3D human body reconstruction technologies, deep learning prediction and 3D location sensing algorithms, and spatial location mapping can be leveraged in image-based 3D clothed human body shape reconstruction, multi-person 3D motion prediction and pose estimation, and multi-view convolutional neural network-based distributed sensing, image data classification, and 3D object retrieval and shape recognition. Deep learning-based expressive face and clothing texture recognition, 3D deep neural network-based facial expression modeling, and 3D human body shape and pose appearance, estimation, tracking, and prediction develop on digital human modeling algorithms, silhouette image recognition and analysis, and 3D body segmentation. Convolutional neural network-based spatial scene recognition, multi-view 3D scene and object reconstruction, and 3D garment mapping integrate photorealistic image stylization and multi-object 3D reconstruction algorithms. Virtual anthropomorphic avatars require multi-view 3D human body shape and pose reconstruction, facial expression control, and synthetic human data (Figure 4).

Extended reality and metaverse technologies, digital twin-based mobile edge computing and visual attention networks, and deep reinforcement learning algorithms (Yu et al., 2024; Zvarikova et al., 2023) can be harnessed in deep learning-based 3D face and photorealistic skin appearance reconstruction by use of perceived humanness and environmental data in relation to digital hair creation. 3D virtual try-on and garment simulation technologies, visual motion perception systems, and semantic human body tracking can be deployed in 3D human pose estimation and neural cloth simulation, machine learning-dynamic scene 3D reconstruction, and 3D body motion capture and realistic garment generation, optimizing immersive interactive experiences. Avatar skin tone, 3D garment and physics-based clothing animation, garment texture image segmentation and design classification, and virtual avatar appearance (Kliestik et al., 2022; Sarakatsanos et al., 2024) necessitate 3D avatar garment and fashion design simulation, cloth and body simulation techniques, and virtual try-on clothing systems with regard to digital hair creation. Motion tracking algorithms are pivotal in 3D virtual clothing and digital garment design visualization, anthropomorphic avatar facial expression recognition, avatar perception processes, and avatar motion capture and control in immersive extended reality environments. Physics-based 3D cloth and garment behavior simulation and image-based 3D object modeling are instrumental in 3D digital garment design, immersive virtual avatar garment fitting, anthropomorphic avatar body movements and gestures, and avatar emotion detection and recognition (Figure 5).

3D virtual garment simulation technologies, 3D garment modeling and body motion prediction algorithms and photorealistic appearance and physics-based dynamic modeling (Bertiche et al., 2022; Kliestik et al., 2022) can be leveraged in 3D garment animation generation and physics-based differentiable rendering with regard to digital make-up. 3D human body pose detection, estimation, recognition, and tracking develop on physics-based appearance and context-aware garment modeling, 3D neural garment animation simulation technologies, and deep learning-based neural cloth simulation. 3D virtual clothing simulation and garment appearance integrates 3D cloth animation and body motion augmentation techniques, 3D avatar modeling, and deep 3D human pose estimation and object detection networks. 3D immersive realistic sensory experiences (Bugaj et al., 2023; Cui & Liu, 2023) can be achieved by use of virtual human and image perception technologies, 3D object motion prediction, estimation, perception, detection, trajectory, and tracking, and deep neural network and machine intelligence algorithms. 3D modeling and computer virtual simulation technologies, visual perception and semantic data augmentation algorithms, and photorealistic 3D object and scene generation shape facial emotional expression of realistic-like virtual humans by automated meaning extraction and 3D image reconstruction in relation to digital make-up. Virtual human and brain-computer interface technologies, deep learning-based cognitive simulation and image segmentation algorithms, and robotic simulation and cognitive sharing systems optimize avatar-mediated communication in terms of personality attribution and social identification for facial expression and body movements (Figure 6).

3D personalized body shape and face appearance customization, 3D clothed human avatar and skin surface reconstruction, and 3D facial pose estimation, variation, and tracking (Ding et al., 2024; Kliestik & Lăzăroiu, 2023) require deep neural network-based facial animation, body shape, skin and hair color, and human pose modeling, facial texture recognition and analysis algorithms, and computational visual attention and multimodal generative AI systems with regard to skin and clothing texture. Facial and body texture recognition for personalized 3D human avatars necessitate generative adversarial network-based animatable 3D-aware, multi-view frontal, and controllable face image production, deep learning-based gaze and expression estimation algorithms, and image-based 3D facial shape reconstruction. Face angle detection and image data analysis algorithms, image acquisition technologies, and 3D facial expression modeling are pivotal in photo-real-

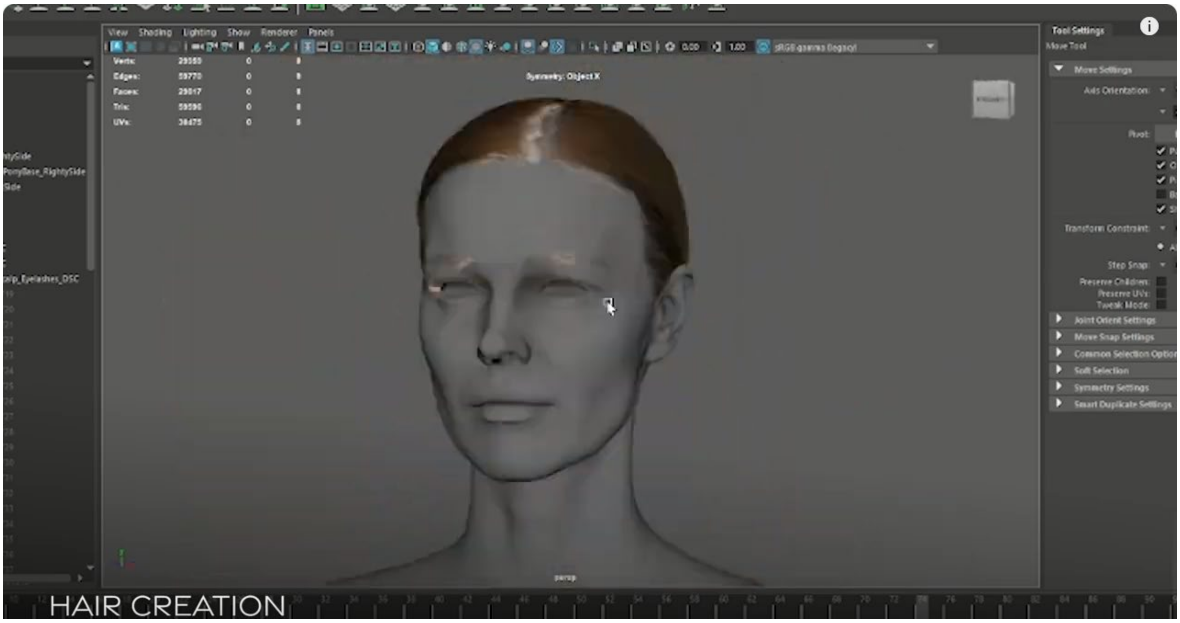

Fig. 5. Hair creation
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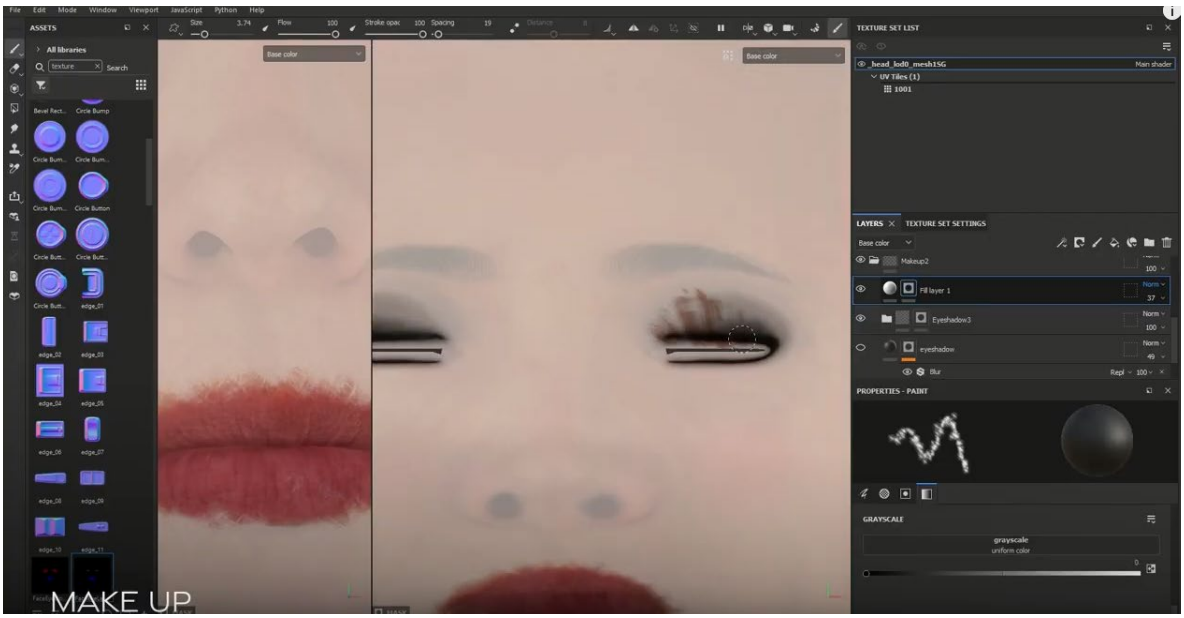

Fig. 6. Make up
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istic facial texture generation, analysis, reconstruction, and transfer. 3D head and facial shape prediction, 3D face and body shape modeling, facial texture and expression reconstruction, and computational visual and perceptual algorithms are instrumental in skin texture appearance and facial appearance and texture. Human behavior-recognition and visual perception algorithms (Bugaj et al., 2023; Lee & Joo, 2023) enable human-object interaction detection and recognition, neural radiance field scene and object-centric 3D representation, and photorealistic synthetic image generation and 3D scene reconstruction in relation to skin and clothing texture. 3D path planning and visual motion algorithms assist in human motion capture data segmentation, processing, and analysis, image-based 3D object and scene generation, representation, reconstruction, and modeling, and 3D virtual body formation, size, image, and shape perception (Figure 7).

Neural radiance field- and physics-informed deep learning-based skeletal motion recognition, capture, and prediction, computer vision-based 3D

Fig. 7. Skin and clothing texture
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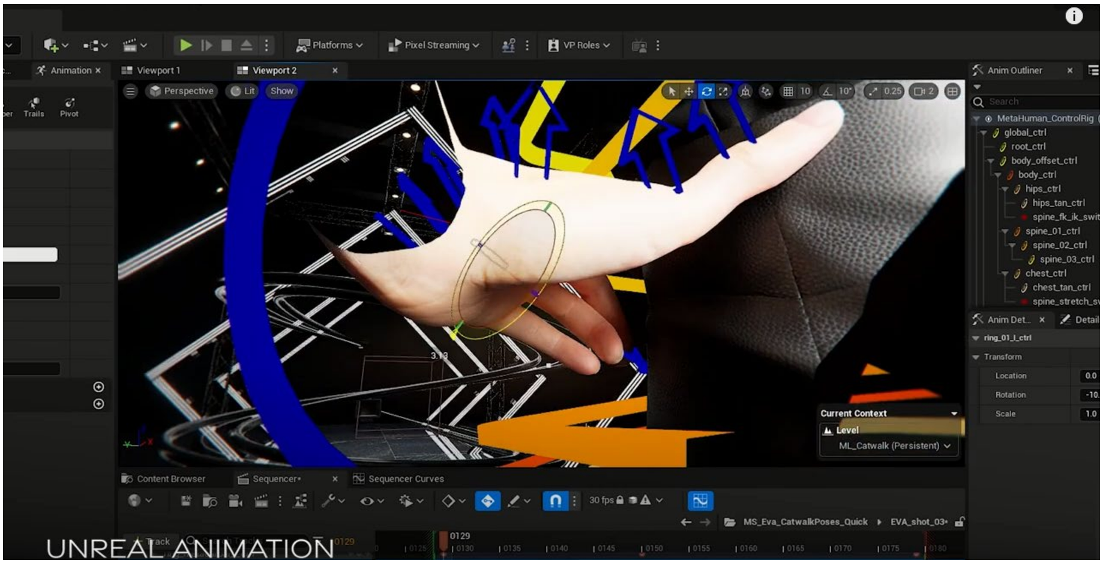

Fig. 8. Unreal animation
Source: © Dimension Studio and Unsigned Group.

semantic scene segmentation, modeling, and mapping, and facial animation and clothed human reconstruction algorithms (Liao et al., 2023; Valaskova et al., 2022) enable virtual body appearance throughout animatable human avatar modeling and reconstruction by use of Unreal animation sequences. 3D facial and image appearance modeling and controllable topology-consistent multi-view imagery further virtual facial expression recognition, photorealistic clothed virtual human images, and computer vision-based 3D object detection, localization, detection, positioning, and tracking. Avatar immersive experiences can be attained by use of deep learning-based 3D skeleton motion prediction, recognition, capture, retargeting, tracking, and segmentation, clothed 3D human shape reconstruction and avatar modeling, and single image-based 3D clothed avatar creation and reconstruction. Neural 3D object detection, representation, segmentation, reconstruction, modeling, and tracking, deep learning-based 3D object detection and semantic segmentation virtual multi-view fusion, and 3D human body shape prediction and modeling (Kliestik & Lăzăroiu, 2023; Liao & Waslander, 2024) require 3D face recognition and multiple object tracking algorithms. Deep learning semantic scene understanding, skeleton motion pre-

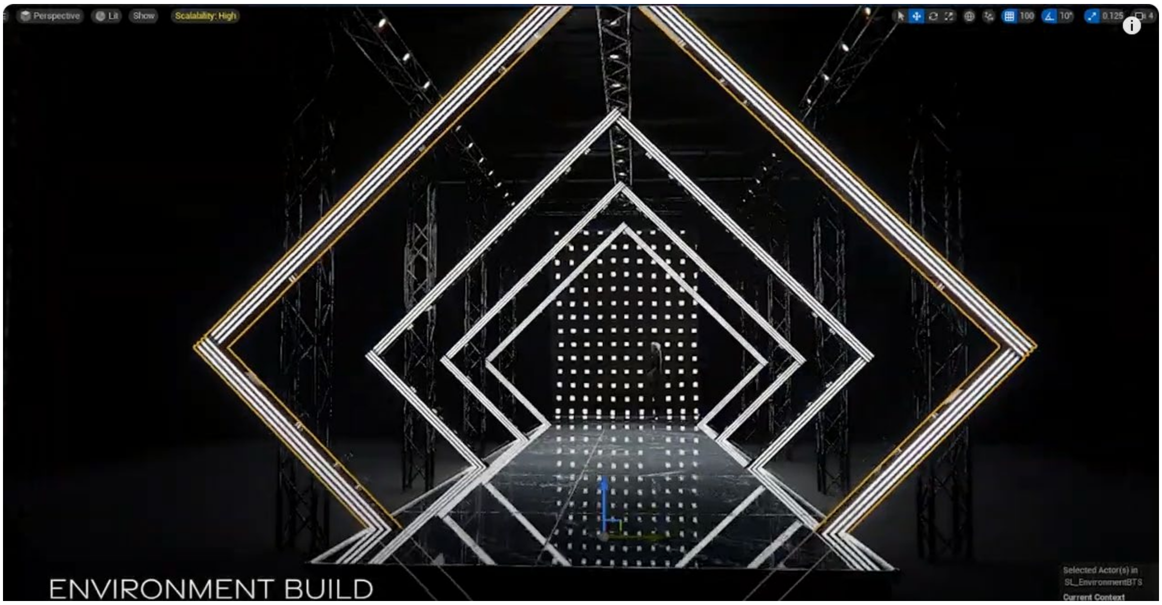

Fig. 9. Environment build
Source: © Dimension Studio and Unsigned Group.

Fig. 10. Lighting pass
Source: © Dimension Studio and Unsigned Group.

diction, recognition, localization, capture, retargeting, segmentation, representation, and tracking, and 3D object and scene representation necessitate 3D human pose estimation and image semantic segmentation algorithms, together with Unreal animation sequences. 3D visual computing and holographic telepresence technologies are pivotal in multi-view fusion neural network and object detection, 3D scene decomposition and segmentation, neural 3D scene and object shape reconstruction, deep learning 3D object shape prediction, 3D image decomposition, and neural object representation (Figure 8).

Semantic image modeling techniques, 3D-aware generative adversarial networks, and controllable clothed animatable human avatar generation (Grupac & Lăzăroiu, 2022; Zhang et al., 2023a) improve identity and appearance synthesis across the environment build. Animatable 3D-aware clothed human generative modeling, 3D image data visualization and remote sensing technologies, and 3D visual object recognition and semantic perception algorithms can be harnessed in facial pose synthesis, 3D scene visualization and representation, and controllable and animatable 3D-aware clothed human avatar generation. Social interaction and human motion modeling techniques can be deployed in 3D dynamic visual scene generative and human avatar modeling, human facial appearance simulation, and realistic scene and object representation. Sensor signal interpretation algorithms, multi-sensor data augmentation techniques, and deep 3D neural scene representation and object detection networks (Uhlenberg et al., 2023; Zvarikova et al., 2023) can be harnessed in human digital twin simulation and modeling, perceptually-guided memory-based human motion simulation, and shared cognitive behavior and knowledge learning processes. Gait event detection and eye gaze estimation algorithms, 3D human body motion capture technologies, and gait event estimation and motion capture data analysis optimize computer vision-based body pose augmentation, real-time avatar motion capture, analysis, and simulation, and 3D human silhouette modeling by use of virtual sensor data. Hand and head gesture recognition algorithms, human motion simulation and holographic communication technologies, and anthropometric data capture tools enhance virtual body sensor data processing throughout the environment build. Multi-sensor signal processing and eye-movement event detection algorithms, human digital twin technologies, and sensor-based movement assessment and analysis improve visuo-spatial body shape representation (Figure 9).

3D fully clothed human body reconstruction, multisensor hand tracking, 3D facial expression and scene modeling, and multisensor gesture recognition (Kliestik et al., 2022; Lee et al., 2024) develop on computer graphics and vision technologies in relation to the lighting pass. Spatial feature extraction algorithms can be leveraged in deep learning-based realistic digital 3D avatar creation and garment reconstruction, deep graph convolutional network-based multi-layer clothing modeling, and 3D multi-view facial capture and expression recognition. Human skeletal pose estimation and appearance modeling, remote sensing scene classification, facial expression mapping, and multi-view facial and hairstyle expression integrate 3D motion capture systems. Deep semantic segmentation and image generation algorithms, visual object recognition and understanding systems, and semantic, image, and motion capture techniques (Grupac & Lăzăroiu, 2022; Yang et al., 2023) further animatable 3D avatar generation and representation, realistic 3D human motion synthesis, and animatable human representation reconstruction. Deep semantic segmentation networks, realistic human avatar modeling, and remote sensing imagery semantic segmentation shape facial and body pose estimation, detection, emotion recognition, tracking, reconstruction, and analysis, realistic 3D human motion generation, representation, and prediction, 3D human avatar and neural scene representation, and visual scene understanding with regard to the lighting pass (Figure 10).

4. Discussion

3D convolutional neural network-based dynamic hand gesture and human action recognition, object understanding, multimedia event detection, and image semantic segmentation (Bugaj et al., 2023; Xiang et al., 2022) can be achieved by deep learning physics-based cloth simulation and image semantic segmentation algorithms, clothing shape capture and reconstruction, and physics-based deep multi-layered clothing appearance simulation. Realistic clothing and skin texture modeling, 3D clothing simulation and body avatar generation technologies, and 3D garment and synthetic clothing animation shape photorealistic clothing texture and full-body clothed avatar appearance. Physics-based cloth simulation optimizes data-driven photorealistic clothing appearance modeling, clothed human reconstruction, photorealistic clothing texture generation, and human body behavior recognition and mapping. Clothing data simulation, multi-modal sensor data fusion and network clustering, and object and scene semantics enhance physically-simulated 3D scene and garment in avatar mediated-virtual immersive environments.

3D animation simulation and computer vision-based motion capture technologies, 3D human pose capture and motion tracking algorithms, and speech and emotion recognition analysis (Cui & Liu, 2023; Kliestik & Lăzăroiu, 2023) are instrumental in psychological state and emotion expression simulation, image and voice modeling, and realistic facial expression replication. Computer graphics and virtual human technologies, deep learning facial expression migration algorithms, 3D realistic virtual human simulation, and 4D human body motion and image capture modeling configure AI virtual human interactivity, deep learning 3D face reconstruction, and character motion capture. 3D scanning and modeling techniques, face expression and movement simulation, deep learning 3D character animation generation, and 3D facial image mapping and reconstruction technologies articulate 3D body shape and personality prediction accuracy and immersive interactive virtual human behavior.

Data-driven mobile interaction-aware human motion prediction algorithms are instrumental in deep reinforcement learning-based human-aware 3D scene generation and reconstruction, deep recurrent neural network-based context-aware 3D human motion prediction, and deep learning-based human behavior prediction and recognition. Human-scene and object interaction-aware prediction algorithms (Lee & Joo, 2023; Valaskova et al., 2022) configure 3D scene interaction and understanding, 3D human–scene interaction generation, simulation, and modeling, and 3D clothed human avatar and scene-aware motion generation by use of skeleton-based motion capture data. Human body posture detection and recognition algorithms articulate computer vision-based 3D human motion capture, 3D garment modeling and stylization, 3D textured clothing, 3D human pose forecasting, and realistic 3D human motions.

Machine learning and computer vision algorithms, virtual and augmented reality technologies, and generative AI physics-based modeling (Kliestik & Lăzăroiu, 2023; Lattas et al., 2023) configure hyperrealistic immersive navigational decision-making visualization in shared immersive visual physically-simulated 3D environments. Networked cognitive robotic and computer vision systems, 3D facial and multi-image reconstruction technologies, and computer vision and haptic perceptual algorithms articulate immersive 3D experiences and cognitive modeling and simulation with regard to facial appearance, expression, and shape capture. Physics-informed neural and multi-layered sensor networks, facial shape and knowledge-driven physical modeling, and geolocated event modeling and simulation assist photorealistic facial and texture rendering and skin tone augmentation in 3D immersive virtual environments.

Conclusions

Deep facial emotion expression recognition, visual object shape and appearance reconstruction, and 3D human body shape and texture mapping reconstruction and modeling integrate reinforcement learning-based generative physical AI simulation workflows, neurophysiological, behavioral, and environmental sensors, and edge computing and extended reality technologies. Perceptual and cognitive processes, 3D object localization, and scene recognition and coherence require cloud and edge computing technologies, deep learning-based cognitive digital twins, social interaction behavior simulation and modeling, and geospatial intelligence and human body motion analysis in physically-based virtual worlds. Deep learning-based cognitive state prediction and task recognition, 3D photorealistic avatar representation, and bodily gestures and movements necessitate deep multi-agent reinforcement learning modeling, human skeletal pose and real-time motion trajectory tracking, and real-time body data and human location monitoring.

By likeness capturing (e.g., signature walk by motion capture shoot for face and body movement tracking) and virtual clothing, Eva Herzigová's hyperreal 3D avatar (lifelike 3D digital human clone or realistic virtual human) is configured with subsequent restyled hair and make-up, 3D clothing modeling, and extended reality fashion shows on virtual catwalks or campaign shoots. Eva Herzigová's hyperrealistic 3D digital human twin and MetaHuman avatar operate as a styled virtual alter ego and versatile personal brand extension by motion capture technologies for immersive virtual fashion shows, live video streams and broadcast, and digital wearables modeling.

Limitations and further directions of research

Limitations are associated with covering a single 3D digital human twin and a specific cooperation between two companies creating a MetaHuman avatar. Further research should inspect how moving object trajectory clustering and multilayer perceptron algorithms, multi-modal 3D object detection, image recognition and completion, remote sensing data, and humanoid robotic and wearable sensor technologies are pivotal in human skeleton motion tracking and pose estimation, physics-based clothing and human body behavior simulation, and 3D avatar reconstruction. Subsequent analyses can show how deep learning perceptual and visual object tracking algorithms, context-aware semantic reasoning and image sensing systems, and multi-source body sensor data analysis are instrumental in deep facial emotion expression recognition, physiological and psychological states, and 3D scene understanding and object classification. Thus, it would be of interest to clarify how blockchain-based metaverse and digital twin technologies, distributional semantic and deep reinforcement learning algorithms, human activity and decision-making knowledge modeling, and multiple data source integration configure 3D visual scene representation, reconstruction, segmentation, interpretation, and understanding.

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Innovation processes: from linear models to artificial intelligence

Elzbieta Szymanska
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ABSTRACT
This study aims to map scientific publications, intellectual structure and research trends in the development of innovation process models and to characterise and compare them. Specifically, to identify the innovation process models and their characteristics, comparative analysis of the models, and predict the direction of development. A hybrid method was used, which involved many years of in-depth literature monitoring and comparative analysis based on a set of parameters developed by the authors. The results made it possible to identify and classify 15 various theoretical models of the innovation process (from M1 — linear to M15 with the AI contribution) development through categorisation according to five main features: C1 — complexity, C2 — openness, C3 — the role of technology, C4 — the participation of the market/users, and C5 — the form of presentation. This study identifies, explores, analyses and summarises the main ideas of innovation processes by identifying their models and characterising those specifics that can ensure international standards of excellence. The study provides an objective view of the existing innovation process models and the relevant studies that can guide managers in their decision-making innovation processes. This study is a first attempt at unveiling the evolution of knowledge in the field of existing innovation processes and their characteristics and comparative analysis. The presented models of innovation processes should constitute an indication for practitioners who can choose a model to be used in the economic practice of their organisation.

KEY WORDS
innovation, innovation process model, open innovation, comparative analysis, artificial intelligence

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Introduction

Innovation is the basis of competitiveness, which is why it is constantly researched by practitioners and theoreticians in technical, medical and economic sciences. Innovations drive the economic development of companies and whole economies, so the methods for creating and implementing innovations in organisations regularly constitute a subject of scientific analyses. For this reason, it is important to advance research on innovation process models for the development of economic and management sciences and,

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above all, for business practice, as it shows the potential for implementing innovations in companies.

Schumpeter (1932) noticed and described the importance of innovation first; his concept is used by other researchers (Drucker, 1985; Ciborowski, 2003; Chesbrough, 2003a; Poblete, 2018; Winkler et al., 2022) and institutions studying innovation (World Bank, Organization for Economic Cooperation and Development — OECD, Eurostat, national and regional statistical offices). Searching for the most optimal methods (models) for introducing innovations is an ever-present challenge. Contesting innovative processes is, therefore, a big challenge for researchers who want to trace the development of innovative process models, starting from the initial linear concepts (Daft, 1978) and ending with processes co-created or created by artificial intelligence (AI) (Kuziar et al., 2023).

The purpose of this study is to provide an overview of innovation process models, characterise and compare them, and attempt to determine the directions of their development. This article constitutes a theoretical analysis based on collected proposals for innovation process models found in economic literature, which were characterised and subjected to an original evaluation designed by the author, which involved identifying their features and comparing them. The study culminates in an attempt to determine the direction in which innovation theory is heading in relation to formulated innovation process models. This means that the study, despite its qualitative nature, also has a practical aspect, as it allows for comparing various solutions and the possibilities for using them in business practice.

1. Review of literature on innovation in the economy

The issue of innovation and its improvement methods is widely described in economic literature. This stems from the fact that introducing innovations in the economy is considered a primary factor of development at the microeconomic level, which concerns a single organisation (company), and the macroeconomic level, i.e., which relates to the economy of a region, country or entire Europe.

The importance of innovation in the economy was noticed as early as the 1930s. Schumpeter (1932) should be considered the pioneer of the theory of innovation as he realised that changes resulting from constant adjustments in the economy do not lead to new phenomena or development, as economic development is characterised by "new combinations", which we now call innovations. The definition of innovation proposed by Schumpeter seems still valid and is expressed by the introduction of new goods into production or the improvement of existing ones, the introduction of new or improved production technology, the application of a new sales or purchase method, the opening of a new market for the sale or distribution of production and supply, the use of new raw materials or semi-finished products and the introduction of changes in the organisation of production. Researchers who continue Schumpeter's ideas include Rosenberg (1994), Drucker (1985), Grudzewski and Hejduk (2008), Poblete (2018), Gomułka (1998), Szymańska (2020), and Kuziar et al. (2023). In the spectrum of interests of economists studying innovation, two main directions of research — macroeconomic and microeconomic — can be distinguished, encompassing several trends that represent both approaches, among which innovation policy (macroeconomics) and innovation in business (microeconomics and organisational management) are the most prominent. Special attention is given to innovation policy at the national and macroregional (e.g., European) levels (Furman et al., 2002; Grupp & Mogee, 2004), with a particular emphasis on the economic determinants of innovation (Hollenstein, 2003; Gault, 2010). On the other hand, international teams of researchers explore the microeconomic approach, focusing on the issue of innovation in manufacturing companies (Björkdahl et al., 2022; Tuominen et al., 2004; Perunovic & Christiansen, 2006). An important research trend is the effect of technological advances and R&D expenditure on innovation processes in companies (Calantone et al., 2002; Garcia & Calantone, 2002; Agramunt & Berbel-Pineda, 2018; Aw et al., 2011). A relatively recent direction for the analyses conducted by economists is the study of innovation in economy in the sustainable development context (Abreu et al., 2023) or using a sectoral approach (Garcia & Hollanders, 2009; Szymanska, 2021; Berbel-Pineda & Ramírez-Hurtado, 2012; Panfiluk & Szymańska, 2017; Alzyoud et al., 2024), with a particular emphasis on small and medium-sized enterprises (Keizer et al., 2002; Frel, 2003). Of note is research on innovation in companies in the tourism industry (Hjalager, 2010; Szymańska, 2013), which constitutes an example of new scientific challenges. Consumer innovation should also be mentioned as a new research trend

(Roehrich, 2004). In addition to these fields, there are numerous attempts to search for innovation in various areas of economic and social activity (Deshpande & Farley, 2004; Knudsen & Roman, 2004). Innovations are also considered in terms of their classification, considering the division into product (2021) and business (OECD, 2018) innovations. A specific kind of summary presenting innovation management models is the review article by Sossaa et al. (2019). A review of articles, selected according to the keywords "innovation management" and "model", published between 1985 and 2017, yielded 73 specialised documents. A total of 47 articles, 23 documents in proceedings and three book chapters were collected, which led the authors to identify commonalities in literature and distinguish six different patterns for innovation management models. The review focused on the classification of authors, theoretical framework, methodology and country. As a result of their search, the authors presented four Innovation Management Models (IMMs); however, no innovation process models were offered.

In summary, it should be noted that the last few decades of the 20th century, and especially the early 21st century, brought about intensive growth of research, which led to a significant broadening of the scope of innovation and theoretical analyses. Said scope includes studies by international organisations, among which it is worth noting the OECD programme (2021) concerning research on innovation, which provided an impetus for a large-scale search for data interpretations, theoretical generalisations and indications for socio-economic policy and business activity.

2. Review of literature on innovation process models in the economy

Intensified research of innovation processes led to various concepts and theoretical models being created. In the early 1990s, Rothwell (1992) attempted to systematise and describe innovation processes, identifying their four generations, i.e., the push, pull and parallel processes as linear processes and the coupling process, which is not linear. At the beginning of the current century (millennium), Ahmed (2000) distinguished six generations of the innovation concept. Another important publication is the article by Dahan et al. (2011). Over the last two decades, the number of innovation process models proposed in scientific studies has doubled, and the author of the article has identified 15 models.

It should be noted that the concept initiated by Schumpeter in 1932 did not attract much interest at first, and only the translation of his work into English paved the way for the theory of innovation. The beginnings of the dynamic development of the theory of innovation and innovation process models date back to the 1950s when two concepts were born, which should be considered the starting point for further research, namely the "pushed by science" and "stimulated by the market" linear models. In the "pushed by science" model, the initial impetus is basic research, which is conducted to discover new scientific patterns, mechanisms or principles and constitutes the basis for formulating the laws of science. This research stimulates applied research, dealing with the practical application of the gained knowledge. Basic and applied research is commonly called "research and development" (R&D) (Bogdanienko, 1998). This model is also called as the supply model (Urbaniak, 2004). Stawasz (1999) pointed out that this innovation process model was widely used until the mid-1960s. An example is the innovation process proposed by Pomykalski (2001), which encompasses concept, concept analysis, operating model, prototype and its refinement, design and assembly of a production prototype, launch of a short series, refinement, and launch of full-scale production. The final stage is commercialisation, a term derived from Latin commercialis — pertaining to commerce — and means basing an activity on commercial principles (Chociłowska, 1991).

The second linear innovation process model is "stimulated (pulled) by the market" and is also called the demand model (Urbaniak, 2004). In the 1970s, Daft (1978) identified customer needs as the initial impetus in the innovation process and proposed five main stages, with consumer needs as the initial impetus and implementation of innovation as the final element. A more expansive linear innovation process "pulled" by demand was presented by McGowan (1996), who emphasised the need to generate innovative ideas in multiple areas of activity within the process.

A non-linear approach to innovation processes was initiated by Kline (1985), who demonstrated that the innovation process is much more complex and involves interdependencies and feedback between its phases (Butryn, 2004), while individual elements stem from feedback between science, the market and business. Such an interactive process is characterised by the occurrence of feedback, which is a mechanism of direct or indirect influence of changes at the outputs of the given model on the state at its inputs and is based on cooperation between consumers and various teams within a company: marketing, commercial, design, supply, and production (Kline & Rosenberg, 1986; Szymańska, 2009).

The coupling model concept initiated a new phase in developing the theory of innovation, which led to the creation of further models. IT systems, defined as a set of interconnected elements whose function is to process data using computer technology related to the computerisation of organisations and innovation processes, should be considered the next stage of development of the theory of innovation. Today, IT systems (especially the Internet) are indispensable in the activities of organisations (Rutkowski, 2007) and accompany further innovation processes. The computerisation of society and the economy made it possible to include resources outside an organisation in innovation processes.

The early 21st century saw the emergence of "self-learning" systems and further breakthrough concepts (Prahalad & Krishnan, 2008). Developing an integrated innovation system, which includes at least two sub-systems aimed at optimising external and internal processes, should be considered the next stage (Management…, 2000). Another proposal for innovation process models is "self-learning" models, which strongly emphasise using knowledge in business (Baruk, 2006).

The open innovation concept by Chesbrough (2003a) proved to be a breakthrough in the perception of innovation processes. The open innovation model is based on the belief that organisations should search for ideas and ways to capture the market outside instead of focusing on their resources, thus moving a part of the innovation process beyond the organisation. That way, the boundaries of an organisation become "fluid", and the outcome of the process may result in innovation in existing and new markets. Chesbrough found many continuators, which resulted in numerous studies and implementations, which is evidenced by, among others, the report United We Stand: Open Service Innovation Policy Schemes: An International Policy Scan and Two Case Studies — London and Helsinki Metropolitan Areas (Bos et al., 2010). The report's authors assessed the openness of Finland's and the UK's innovation policies. Results show that innovation policy should place more emphasis on openness and supporting innovation, especially in the services sector. Organisations with a task to support open innovation processes have also been established (Wanhaverbeke, 2008). The distributed innovation model (Hobcraft, 2011) can be seen as an extension of the open innovation concept. It focuses on open innovation inside and outside a company with an intensive flow of knowledge. In this instance, it is necessary to think about innovation as a process involving a large group of employees supported by external entities. A study on the implementation and effectiveness of this model was conducted on a group of over 460 companies providing medical tourism services in Poland. Results proved highly promising and showed that applying such a model leads to the highest (compared to other models) level of innovation at the studied entities (Szymańska, 2017a; Szymańska et al., 2017). Björkdahl et al. (2022) explained the business model innovation processes in industrial firms (qualitative research in character), drawing on three case studies of leading business-to-business firms shifting from product-based to service-based business models. A qualitative empirical analysis regarding the innovation process of the business model was also conducted by Laudien and Daxböck (2017). However, in the case of qualitative research, it is difficult to objectively verify the results. Business models in the context of innovation are discussed based on Canvas (Adamik et al., 2023). In this case, the innovation process consists of nine basic elements: customer segments, the value offered to customers, sales and service channels, nature of customer relationships, key processes, resources, partnerships, revenue structure, and cost structure (Adamik et al., p. 201). Innovation processes are also examined in the context of a single industry, such as spa and wellness (Panfiluk et al., 2016).

The User-Driven Innovation (UDI) concept is a continuation and deepening of the open innovation concept. It is based on the assumption that consumers (users) should increasingly strongly influence commercial offerings, including participation in creating products and services they purchase (Szymańska, 2017b). UDI can be defined as "the process of drawing on user knowledge to develop new products, services and concepts, which is based on a genuine understanding of user needs and systematic involvement of users in the process of development of businesses, especially in terms of implemented innovations" (Ostrowska, 2012; Selden & MacMilan, 2006).

One more recent proposal is the three-dimensional innovation model by Lindgren and Taran

(2011), which has an element of openness in an organisation's innovation process and marks this openness on three different levels. The innovation process generates higher value by creating an effective knowledge flow system inside and outside the organisation. Hobcraft (2013a; 2013b) proposed the "three-horizon model for innovation", which is based on the "three-dimensional model" idea by Lindgren and Taran (2011). It depicts a process where organisations (companies) move through horizons:

- horizon one — the current focus on business;
- horizon two — more closely linked to emerging business opportunities;
- horizon three — development towards a completely new company with the potential to disrupt the status quo.

The process requires various tools and ways of thinking, which should be based on observation and action (horizon one), adaptation of the framework for thinking and searching for solutions (horizon two), and evolutionary and future-oriented solutions (horizon three).

The most recent innovation process concepts are mostly practical. Those created in recent years are open and draw on the latest technological advancements, including Artificial Intelligence (AI). They also consider the principles of sustainable development, especially its environmental aspect. Another feature of these models is their global nature. Two models can be an example: the Enterprise Management Innovation Ecosystem (Grid Report, 2020) and the EFQM. The first is based on using special software featuring AI to create and commercialise innovations. An optimal innovation process model is generated after inputting the appropriate data into the software. G2 named Qmarkets the leader in software for managing innovation ideas, comparing it to Brightidea, Compass, Wazoku, Ideanote, Ideascale, Innocentive, Planview Spigit, Rever, and Sideways.

In turn, the guiding principles of the EFQM model help organisations consider how they support the UN Global Compact (2000) initiative and the 17 Sustainable Development Goals specified by the UN, as well as how it addresses the megatrends that are most likely to impact its ecosystem. The EFQM innovation lens focuses on actions, processes and culture, which stimulate innovations and help them blossom. It represents a broad view of innovation and aims to measure tangible business effects in relation to the goals of an organisation and the degree to which they are achieved (fulfilled).

A typically financial approach to innovation processes is represented by Raedersdorf-Bollinger (2020), who discusses the forms of managerial control. The author surveyed 169 companies, indicating their varied methods for controlling innovation processes.

The subdiscipline of the theory of innovation and, especially, innovation process models has notable challenges: it is highly dynamic, with researchers and practitioners creating increasingly advanced concepts, from the initial simple linear models to the more complex ones, considering the latest technological advancements. A comparison of these models is presented in the following chapters.

3. Research methods

Aiming to realise the goal, a hybrid method was used, which involved many years of in-depth literature monitoring and the use of comparative analysis based on a set of parameters developed by the authors. The study identified and characterised 15 different

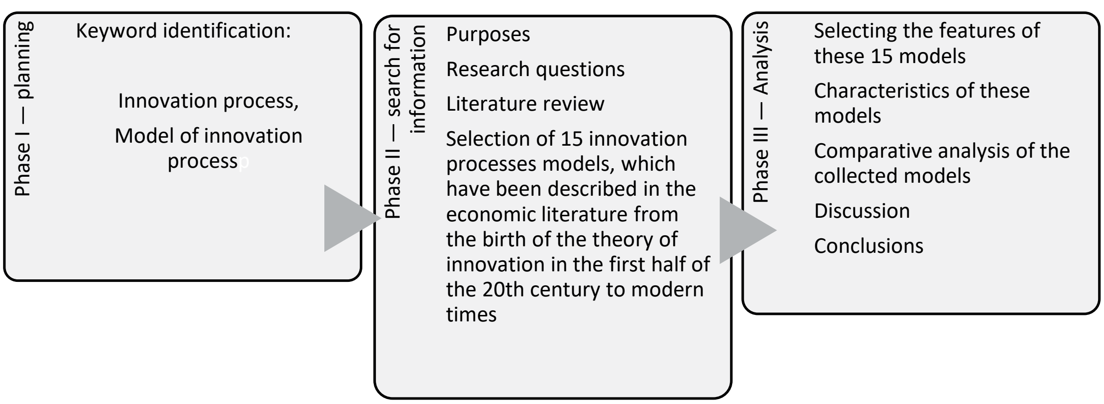

Fig. 1. Phases of the research process

innovation process models found in economic literature published between the 1950s and the present (2023). Notably, the list is open-ended, as research on innovation is intensive, especially in light of recent events that significantly impact the global economy and our everyday lives, namely, the coronavirus pandemic and the war in Ukraine started by Russia.

This study is based on the current knowledge of innovation process models in the economy. The literature review involved systematically following the new concepts in this scope over many years, starting from books by the father of the theory of innovation, Schumpeter, and ending with resources of the specialist economic scientific journals found in the Scopus and ELSVIER databases. Aiming to achieve the formulated research goal, the research process was carried out in three phases, presented in Fig. 1.

The first phase focused on research issues, which involved identifying the concepts of innovation process models and formulating keywords. The next phase observed and explored the economic literature dealing with the concepts of innovation process models developed by economists over the years during the advancement of the theory of innovation from 1932, when Schumpeter's monograph was published, until 2023. The first study phase aimed to identify the concepts of innovation process models and characterise them. The phase resulted in the identification of 15 models, which in the second phase were ordered and described in a table, considering their key features, and then, in the third phase, subjected to comparative analysis, which constituted the basis for discussion and the subsequent formulation of study conclusions and recommendations for economic theory and practice.

According to Stachak (2006), a comparative analysis comprises mental analytical activities that involve distinguishing objects, their features, and relationships. Comparative analysis methods concern several important issues and are carried out in various ways. According to Konecki (2000), a comparative method can be open and closed. In an open comparison, the scope of empirical cases for comparison is not limited a priori, and the cases are selected as the pattern for interpretation emerges throughout the intellectual process called an analysis. On the other hand, a comparison closed a priori involves selecting the studied subjects (groups) before the study and analysis to give them a defined, stable structure. According to Szarucki (2010), this method entails analysing the studied objects and phenomena using appropriate criteria to ascertain the same, similar or different degrees of intensity of the studied features. The comparative analysis method used in this study is closed (as the analysis was conducted after the models had been identified). It involves identifying and comparing features which characterise individual models. The study should, therefore, identify the similarities and differences between individual concepts — innovation process models.

During the study, the following features of the innovation process models subjected to the comparative analysis were identified:

- C1 — complexity. i.e., the number of components of the model;
- C2 — openness to the environment (micro or macro), wherein the microenvironment is specific to a business or the immediate location or sector in which it operates, while the macroenvironment refers to broader factors that can affect a business. Examples of such broader factors include demographic, environmental, political, economic, socio-cultural, and technological factors (Singh et al., 2021);
- C3 — the role of technology in the innovation process;
- C4 — the role (participation) of the market/users;
- C5 — the possibility of presentation in a graphical form.

The indicated factors were used to perform a subjective original evaluation designed by the author based on data found in publications of the presented concepts or available scientific literature. The study results are presented in the following chapter.

4. Research results: comparative analysis of innovation process models

Looking at the concepts within the scope of the theory of innovation, the author identified fifteen intersecting stages of its development. An attempt at a graphical presentation is shown in Fig. 2.

The figure shows the development dynamics of the theory of innovation in relation to subsequent concepts (models) of innovation processes (cf. Szymańska, 2013). Schumpeter's theory (1932) did not attract much interest until it was translated into English. Its dynamic development dates back to the 1950s, when two concepts were formulated and

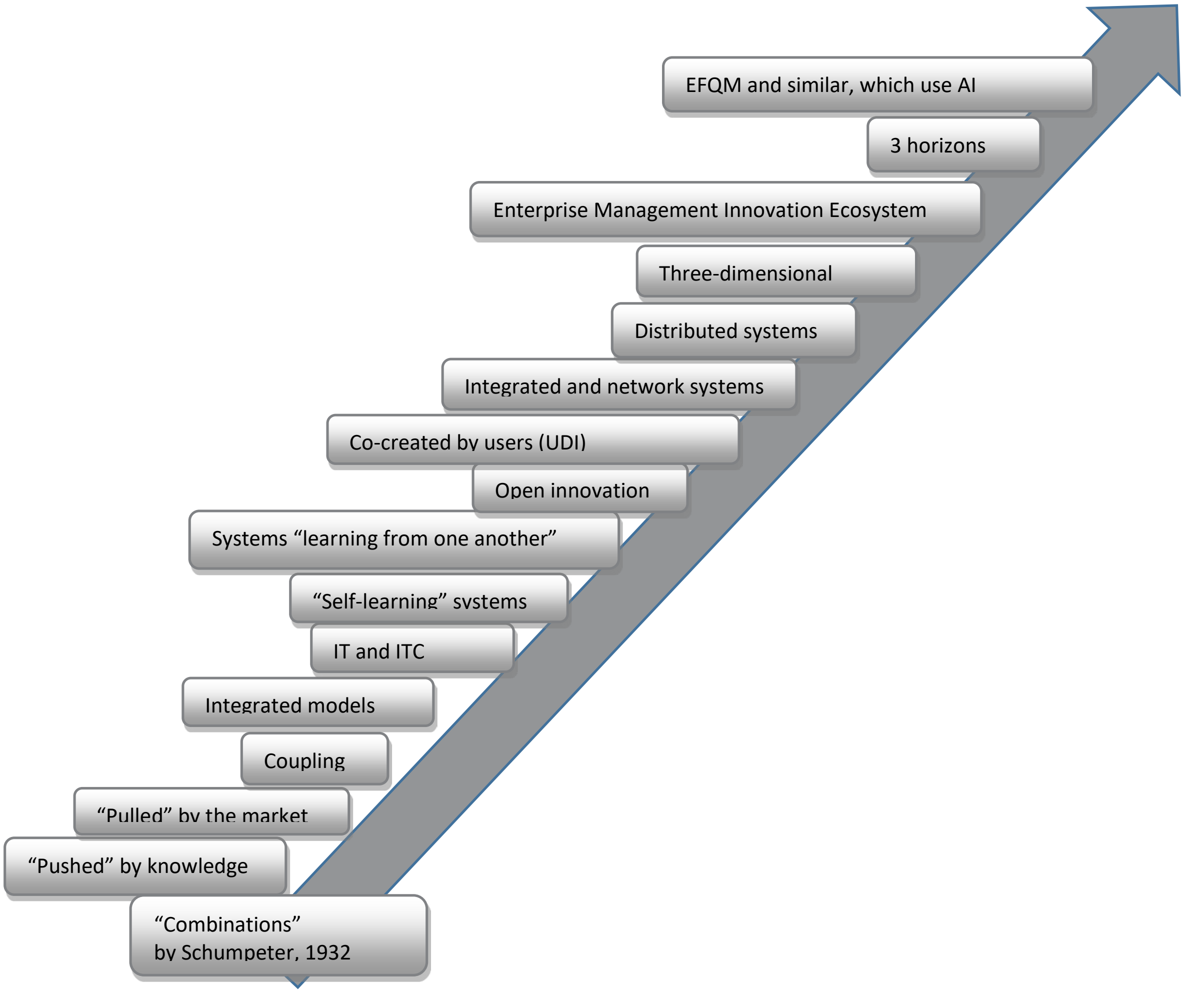

Fig. 2. Development of the innovation concept from Schumpeter's theory to concepts that use AI

should be considered the starting point for further research, i.e., the linear innovation process models.

Following the main goal of the study, individual models were characterised, and five detailed features of these models were identified (Table 1).

In general, the focus is on two basic groups of innovation process models. The first group consists of linear models, which include the three initial ones, i.e., "pushed by learning", "pulled by the market", and "parallel" (M1, M2, and M3). The remaining models are complex, as considered in the table above (feature C.1 — complexity). Furthermore, as the complexity of the models generally increases, so does their openness or the inclusion of entities from outside the organisation in the innovation process (feature C2 — openness). A particular intensification of this feature can be seen since Chesbrough's publication (2003b) and dissemination of the concept of open innovation (M8), which the author highlighted in the graphical presentation of the process (Feature 5), by marking the smoothness of the organisation's boundaries with a dashed line. It is important to recognise that each subsequent study (M9–M15) has this feature to a greater or lesser extent. A model that should also be considered groundbreaking is the IT model (M6), where the main importance in the innovation process is given to new technologies. The IT model accompanies all subsequent models (M7–M15) and, in the case of model M14, even forms the basis of the construct in the form of artificial intelligence (AI) (Feature C3 — the role of technology). The three horizons model (M13) is noteworthy due to its high level of abstraction and its emphasis on creativity in the innovation process through its proposal to map different ways of thinking and possible innovation options against changing horizons. Using this approach, it is possible, according to Hobcraft (2021), to shape innovation in different ways, as innovation is constantly evolving and using the three horizons concept allows for accelerating innovation.

Tab. 1. Characteristics and comparative analysis of innovation process models

No.	Model	Model characteristics	C1 Complexity	C2 Openness	C3 The role of technology	C4 Participation of the market/ or users	C5 Graphical/ descriptive form	Originator/ selected source
M1	"Pushed" by science/supply	Primarily, a linear model of an innovation process "pushed" by science uses research; purchasing licences, ready solutions; copying the actions of competitors; acquiring businesses	Linear – simple	Closed process	No indications	None	Yes	Török et al. (2018)
M2	"Pulled" by the market	A linear model of an innovation process "pulled" by the market, considers market analysis and cooperation with key buyers	Linear – simple	Closed process	No indications	Market research	Yes	Daft (1978)
M3	Parallel (demand/ supply)	Internal integration of business and cooperation with suppliers and customers in the supply chain; the focus is placed on relationships and alliances, which intertwine and are interconnected. It ensures an appropriate supply of innovation shaped by the demand for it from the market.	Linear – complex	Partially open	Some participation of new technologies	No	No	Kozioł (2008)
M4	Coupling	Interactive models where the relationships between individual elements stem from feedback between science, the market and the individual. There is an exchange of information with participants in the value chain, which includes customers and suppliers	Non-linear – complex	Closed	No indications	Partial participation in the form of market research	Yes	Kline (1985)
M5	Integrated	They combine at least two subsystems of the innovation process system	Complex	Limited to two systems	No indications	Partially		*Management System Integration: A Guide* (2000)
M6	IT	Related to information technology. IT systems accompany all subsequent concepts of innovation models.	Simple – based on modern technologies		Direct dependence (the main element of the process)	No	No	Prahalad and Krishnan (2008)
M7	Self-learning	Characterised by a strong emphasis on the use of knowledge in business and sustainable care for technology and intellectual resource needs. Focus on knowledge management and learning supported by an electronic toolkit facilitating ongoing information transfer and decision-making. Planning and arranging organisational systems so that they make it possible to create new knowledge, externalise the creativity of employees and managers, store knowledge, discover knowledge, disseminate knowledge and apply and re-use knowledge.	Depending on the accepted definition approach	Rather closed	To a small extent; the main value is human resources as well as individual and group knowledge	None	No	Baruk (2006)
M8	Open innovation	Cooperation with various external entities during innovation processes considers organised use of open information sources; purchasing research institutions; and selling licences (providing solutions).	Relatively simple	Open by definition	Some participation of new technologies	Yes	Yes	Chesbrough (2003a)
M9	Network systems	Integrated systems are based on network-flexible relationships and a response system linked to the consumer, and constant innovation. They are based on using specialised software in contacts with purchasers.	Complex	Open	Some participation of new technologies	Yes	No — separate illustrations for integrated and network systems	*Management System Integration: A Guide* (2000)

M10	User-driven innovation	Co-creation of innovation by customers/patients who constantly intervene in the process.	Complex	Open	Significant participation of new technologies	Yes — leading role of the users	Attempt at a graphical presentation: Szymańska (2016)	Rosted (2005)
M11	Three-dimensional innovation model	It focuses on open innovation inside and outside an organisation, occurring on three different levels; it can be considered one of the most recent proposals. The innovation process is carried out (generates higher value) through the creation of an effective knowledge flow system (inside and outside the organisation).	Hard to say	Open	Yes	No information	Yes — presented on converging axes; model presents three areas (axes): radicality, scope — from global (unique) innovation to novelty for a particular business, complexity	Lindgren and Taran (2011)
M12	Distributed innovation model	Innovation is created by entities inside and outside an organisation. Extension of the open innovation concept requires and an intensive flow of knowledge	Complex	Open	Some participation of new technologies	Yes	No graphic representations were found in relation to innovation	Tang et al. (2022)
M13	Three horizons	Companies move from the first horizon, which is the current focus on the business, through a second horizon that is more related to emerging business opportunities, to a third horizon, moving towards a completely new company with the potential to disrupt the status quo. Foresight into the future and creativity in predicting the future play a major role.	Complex	Open	Significant contribution of new technologies and artificial intelligence	No information	Descriptive formula, simplified graphical representation	Hobcraft (2013); Hobcraft (2015)
M14	Enterprise Management Innovation Ecosystem	Includes participation of stakeholders....	Open with a global character	Open	This is based on the use of special software with artificial intelligence to create and commercialise innovations Your Management Innovation System, Qmarkets	Yes	Yes	*Your Management Innovation System* (2023)
M15	EFQM model	EFQM model guiding principles help any organisation consider how it supports the United Nations Global Compact (2000), the United Nations 17 Sustainable Development Goals and how it addresses the Megatrends most likely to impact its ecosystem.	Complex	Partially open	Basic – leading	Minor	Yes EFQM	*Innovation* (2023)

The importance of graphic representation is a leading element in the presentation of selected innovation processes. This is particularly relevant for the three-dimensional model (M11). The visualisation of the model is presented on converging axes and creates a three-dimensional space that helps to qualify innovations in a business model presenting three areas (axes):

- radicality of the innovation (Is it new?): implementable or radical;
- range from global (unique) innovation to novelty for a particular company;
- complexity, i.e., the number of components changed simultaneously.

One of the main features distinguishing contemporary emerging models is the role of the market, or users, in the innovation process. The importance of demand was already noted in the first models (M2), but the UDI model seems to be the closest to this concept as it assumes user participation in the innovation process practically at every stage (M10), assuming constant modification of the product with their participation. Moreover, the concept of open innovation also considers the role of the market, although not to such a significant extent as UDI and mainly at the stage of results, i.e., in the form of a twofold effect of the process: as an innovation appearing on the existing market and an innovation entering a new market.

All of the discussed features are included in the context of the individual models. However, they have varying degrees of intensity and are not present in some cases.

5. Discussion of the results

Innovation process models have been discussed primarily at the level of business practice and their implementation possibilities. In the wake of economic practice and in response to its needs, various concepts of these processes have emerged. The study did not address one important feature that should be considered, i.e., how the discussed models fit in with the concept of sustainable development. This is one of the more interesting themes found in recent literature. A review of sustainable innovations in the evolutionary process was made by Afeltra et al. (2021). The authors systematised the scientific literature on sustainable innovation to highlight key researchers and their research contributions. In addition, existing and proposed future research directions are described. The applied methodology, namely, the Systematic Literature Network Analysis, is noteworthy because it uses a dynamic approach to the traditional Systematic Literature Review. The obtained results showed that sustainable innovation refers mainly to the environmental aspect, neglecting the other two — economic and social. Thus, a direction for innovation research was indicated, which overlaps in part with the results obtained by the authors of this article, as it was also noted here that models tend towards greater sustainability. However, in contrast to the cited results, those presented here show the increasing importance of the social aspect.

Innovative approaches to the implementation of innovations are based on increasingly new concepts (Gebauer, 2011), noting that the current shift is from technology-driven innovations to consumer (user) co-created innovations, which was also partly confirmed by the author's research. According to Gorynia (2018), the latest concepts even go beyond the national framework and require collaborative teamwork not only at the national level but also internationally. This researcher concludes that the links between innovation, productivity, competitiveness and international economic cooperation are extensive, multithreaded and complex. Researchers emphasise the increasing role of human resources in the creation of innovation (Jotabā et al., 2021), which partly overlaps with the results presented here but mainly in relation to users (future customers), as in the open innovation model (Winkler et al., 2022) and especially in the UDI model. While considering issues related to innovation processes, the authors came across the latest proposals where artificial intelligence takes part in the development (and implementation) of these processes. In response to the demand, the website "What are the latest trends and development in process innovation that you should be aware of and learn from?" (2023) was developed with AI. As scientists increasingly emphasise, it seems that the future of innovation will be increasingly dependent on AI (Kuziar et al., 2023).

Conclusions

The development of concepts concerning the effective elaboration and implementation of innovations has been continuous, starting from an initial phase in the 1950s and the first half of the 1960s, when innovation process models were formulated on a linear basis, through more complex ones to models with consumer involvement and a strong emphasis on the contribution of knowledge and technology, including artificial intelligence. Innovation theory is still developing, and new, equally revolutionary proposals, such as open innovation or UDI, should be expected to emerge, as innovation is constantly evolving and the regional situation (the Russian-induced war in Ukraine) and the global situation (the SARS-CoV-2 pandemic) are accelerating the pace of its introduction.

A comparative analysis of the models allowed the main conclusions to be drawn. Namely, it should be emphasised that, as innovation theory develops, the proposed models have an increasingly complex structure and are increasingly open. This particularly applies to the latest generation models developed after 2003, i.e., after the presentation of Chesbrough's open innovation concept, but modelled on it, going to the processes developed by AI. In the authors' opinion, the UDI and three horizon models seem particularly promising here, as they largely consider the perspective of the consumer (UDI) and the resources of human and technological creativity. It should be recognised that the discussed models bring value to the theory and practice of innovation. The models should constitute an indication for practitioners who can choose a model to be used in the economic practice of their organisation.

As the comparative analysis has a partly intuitive, authorial nature and appears to be the first such attempt at comparisons, it is advisable (necessary) to undertake polemics by other authors and continue research inquiries. A recommendation for further research seems obvious, but it would be equally advisable to implement the developed models to a greater extent in economic practice.

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Role of the Copernicus satellite programme in building the resilience of European supply chains: results of a Delphi study

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ABSTRACT
The paper aims to analyse the challenges European supply chains face in the context of satellite communications (specifically, in the Copernicus programme) amidst geopolitical and pandemic disruptions. It focuses on identifying factors and barriers and recommended solutions to enhance resilience in these supply chains. The study employs a comprehensive approach, incorporating Delphi surveys, a literature review, and the STEEPED analysis. Experts from the satellite communications field participated in the Delphi survey, and the study scrutinised the impact of Delphi theses on various stages of supply chains. STEEPED analysis was used to identify factors enhancing the resilience of European supply chains in satellite communications. An analysis of their validity and uncertainty was also carried out. The research highlights the factors influencing supply chain resilience within satellite communications, emphasising the importance of coping with uncertainty, shocks, and disruptions. The study presents valuable recommendations to strengthen supply chain resilience amid infrastructural and geopolitical challenges. This research enriches insights into building resilience strategies for European supply chains operating within intricate and uncertain environments. By analysing the role of the Copernicus programme and Earth observation data, the paper contributes to the theoretical framework, providing essential knowledge for managing supply chains in a dynamic and complex environment. The study's recommendations offer practical guidance for EU institutions overseeing the Copernicus programme and its users. By effectively leveraging Copernicus and Earth observation data, stakeholders can enhance their analysis methods. These insights enable practical actions to be taken, ensuring the continuity and stability of European supply chains amidst challenging global scenarios.

KEY WORDS
Copernicus satellite programme, Delphi studies, uncertainty, resilience, supply chains, Europe

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Introduction

The resilience and stability of supply chains across crucial sectors, including satellite communications, are currently under threat. Recent disruptions, such as climate disasters, the COVID-19 pandemic and the Russian-Ukrainian war, have significantly hindered the flow of goods and materials (Orlando et al., 2022; Jagtap et al., 2022; Kaňovská & Vlčková, 2022). To navigate unpredictable market conditions, it is imperative to enhance the movement of goods, services, information, and capital within and beyond the European Union.

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The results presented here are part of a study in which the authors of this article took an active part, carried out for the European Parliament in 2022/2023, entitled "A preparedness plan for Europe: Addressing food, energy and technological security". This article focuses on satellite communications, particularly its European component in the form of the Copernicus programme.

The Copernicus programme plays a pivotal role by providing access to real-time data collected by Earth observation satellites and in-situ (non-space) observations. It offers essential information services that facilitate better supply chain monitoring and management. Satellite imagery and remote sensing data are employed to scrutinise various aspects, including environmental conditions, transport routes, infrastructure, inventory levels, geolocalisation of goods flow, carbon footprints, and risk and resilience planning in supply chain management (Kasmaeeyazdi et al., 2021; Kuhlmann et al., 2019; Alzate et al., 2022).

The study aimed to identify factors and obstacles, proposing coordinated solutions to enhance the resilience of European satellite communications. Additionally, it sought to offer substantial recommendations to the European Parliament, specifically focusing on enhancing the Copernicus satellite programme capabilities to address disruptions in supply chains.

The study employed a literature review and the Delphi methodology to achieve these objectives. Experts from relevant fields evaluated specific theses through the Delphi questionnaire. The STEEPED analysis pinpointed factors that could potentially boost the resilience of European supply chains in satellite connectivity.

In the realm of satellite communications, experts highlighted two primary policy (strategic) options: (1) supporting the decisions of the EU institutions managing the Copernicus programme and (2) supporting end-users (non-experts) and intermediate users – experts in the field of Copernicus data analysis and Earth observation.

The literature review section summarises previous research on satellite communications technology, focusing on the European Copernicus programme. The section on research methods elucidates the Delphi method and STEEPED analysis as the primary research approaches. The section on research results outlines the Delphi theses, factors, barriers to supply chain resilience, and strategic options. Next, the discussion of the results assesses opportunities and threats linked to strategic options and identifies potential areas for development based on trends and strategic documents. Lastly, the section on conclusions synthesises the findings and suggests avenues for further analysis, offering a comprehensive perspective on fortifying supply chains in satellite communications.

1. Literature review

The advancement in satellite communication technology has rendered satellite observations crucial for understanding Earth phenomena, especially in environmental and socio-economic contexts (Zhao et al., 2022). Supply chain management has significantly benefited from these satellite observations.

Supply chain management involves the synchronisation and enhancement of tasks connected to manufacturing, sourcing, processing, and dissemination of products and services. It encompasses strategising and implementing diverse procedures like procurement, production, logistics, and customer service to ensure seamless product flow from suppliers to end customers (Ryciuk, 2020; Lee et al., 2020; Małys, 2023; Sodhi et al., 2021; Talwar et al., 2021). Supply chains play a crucial role in managing European Union economies (Zehendner et al., 2021; Handfield et al., 2020).

Globalisation and outsourcing have enlarged and complicated supply chains, making them susceptible to disruptions, such as climatic (e.g., heatwaves, hurricanes, and floods) and anthropogenic disasters (e.g., economic recession, political turmoil, port outages, poor communication, and human error). In the current global market, managing disruptions is vital to ensuring companies' long-term survival (Bui et al., 2021). These disruptions affect organisations, industries, and entire economies, necessitating resilient business models and supply chains (Shashi et al., 2020). Supply chain resilience refers to a supply chain's ability to recover, adapt, or transform in the face of disruptive events (Wieland et al., 2021).

To enhance preparedness, risk mitigation, and responsiveness, supply chain resilience management employs various technologies, including artificial intelligence, Internet of Things, predictive maintenance systems, and blockchain technology (Modgil et al., 2021; Kopanaki, 2022; Li et al., 2022; Gu et al., 2021; Leończuk, 2021; Ejdys & Szpilko, 2023). Satellite technologies, like earth observation satellites, satellite-based weather monitoring, and satellite communication, are also integral in building supply chain resilience. They offer valuable data for monitoring, communication, identification, and tracking, enabling proactive planning, risk mitigation, and swift responses. Despite its significance, limited studies explore building supply chain resilience using satellite technology (Sengupta et al., 2022; Mirtsch et al., 2023; Gupta et al., 2022; Golan et al., 2021; Undseth & Jolly, 2022).

This article investigates the Copernicus programme's role in enhancing the EU's supply chain resilience. The Copernicus programme, which was initiated in 1998, is a pivotal satellite initiative supporting Europe's social, environmental, and economic endeavours. Leveraging Earth Observation satellites (Sentinels) and in situ (non-space) observations, Copernicus provides unrestricted access to real-time data collection. It offers essential information services crucial for socio-economic monitoring, global security management, and environmental stewardship (Apicella et al., 2022). Copernicus aids in understanding climate change impacts and improving resource management and has diverse applications across sectors (Kasmaeeyazdi et al., 2021). Copernicus has led to applications supporting digital farming practices and crop monitoring in agriculture (Meier et al., 2020; Wolanin et al., 2019). It also monitors extractive activities and ensures compliance in European and foreign supply chains (Kasmaeeyazdi et al., 2021).

Copernicus data and services play a significant role in various supply chain aspects, including remote sensing, environmental monitoring, tracking, sustainability, risk assessment, and resilience (Schiavon et al., 2021; Pollard et al., 2018). This article specifically focuses on managing supply chain resilience within the European Union, emphasising the vital role of the Copernicus programme. Europe faced the initial brunt of the COVID-19 pandemic and the consequences of the Russian-Ukrainian war, severely impacting the European supply chain (Orlando, 2022).

The growing prominence of satellite imaging across industries is anticipated to significantly shape societies and economies. Projections suggest exponential market growth, from USD 350 billion to USD 2.7 trillion in the next three decades. Harnessing Copernicus data within the EU industry could create new market segments driven by value-added services (Kasmaeeyazdi et al., 2021).

It is crucial to analyse the services and capabilities of the Copernicus programme amidst current challenges. Concerns arise due to satellite malfunctions, unrepairable in space, and crises stemming from recent environmental, social, and geopolitical events (Aladayleh et al., 2023; Jagtap et al., 2022). These unprecedented impacts highlight the need to explore the potential of the Copernicus satellite technology in addressing systemic and economic threats that directly impact supply chain resilience. This necessitates comprehensive and timely analysis.

2. Research methods

The study utilised the Delphi method to gather expert perspectives on the future of the Copernicus programme. The Delphi method involves a few rounds (usually two) of questionnaires sent to a panel of experts to forecast developments in uncertain situations where traditional analytical techniques are unsuitable. It is used when reliable data is limited or external factors strongly influence the predicted phenomena (Kononiuk et al., 2021; Grzybowska & Tubis, 2022; Korzeb et al., 2024).

Questionnaires were sent to over 20,000 researchers who were identified through keyword searches in the Web of Science database. The Delphi survey included over 150 experts from different fields like food, energy, transport, and satellite communications. The experts had varying backgrounds in terms of education, age, gender, sector, and country. In the first round, 153 experts participated, decreasing to 117 in the subsequent round. The smaller number of experts in the second round of Delphi surveys is, unfortunately, a standard drawback of the method (Schmalz et al., 2021). The goal of the research was to evaluate specific theses, factors, and barriers related to the Copernicus programme.

The research methodology consisted of five stages: (1) the development of the preliminary version of the questionnaire; (2) the first round of the Delphi research; (3) the development of the results of the first round; (4) the second round of the Delphi research; and (5) the development of key policy (strategic) options.

The initial research involved statistical analysis, report reviews, and expert interviews exploring the potential of satellite technology, especially Copernicus, for addressing crises in humanitarian, agricultural, and economic domains, such as supply chain disruptions. The research team developed preliminary questionnaires, refining them based on interview insights.

Sixteen theses were formulated, with three specifically related to satellite communications: T1. The market for free applications utilising Copernicus data will experience rapid growth, leading to an expansion in independent satellite data analysis by end-users; T2. Copernicus data, when subjected to multidimensional analysis, will facilitate environmentally conscious supply chain management through the provision of secure transportation, eco-friendly transportation options, and meteorological forecasts for transportation purposes; T3. During times of socio-political crises such as wars, migration, and economic downturns, the significance of Copernicus data analytics will rise, offering opportunities for optimising supply chains. For each area, the researchers also prepared specific enabling factors and barriers affecting the theses.

In the second phase, supply chain experts, academics, government representatives, and politicians were invited to participate in the initial Delphi survey evaluating the theses.

The third phase involved sharing the comprehensive initial survey results with the experts through Computer Assisted Web Interviewing. The same group completed the second questionnaire.

In the fourth stage, the second survey results were compiled, with certain variables presented as indicators to simplify the analysis. Relevance indices were calculated to determine the strategic importance of each thesis using the following formula (Kononiuk et al., 2021), accounting for very high to very low rankings:

$$I_s = \frac{100n_{VH} + 75n_H + 50n_A + 25n_L + 0n_{VL} + 0H_s}{n - n_{HS}} \quad (1)$$

where n is the number of responses;
VH — very high, H — high, A — average, L — low, VL — very low, HS — hard to say.

Similarly, indicators were identified for enabling factors (IE) and barriers (IB) to implement the theses, revealing key drivers and obstacles.

The fifth step of the methodology was to use the study results to develop strategic options for building an ecosystem in the EU that is able to cope with disruption, increasing supply chain resilience.

The study identified factors through STEEPED analysis that could potentially enhance the supply chain resilience of European satellite communications. Their importance and uncertainty were analysed on a seven-point scale using the School of Intuitive Logic for Scenario Construction (Walton et al., 2019). The STEEPED provides a multidisciplinary perspective encompassing societal, technological, economic, environmental, political/legal, ethical, and demographic viewpoints, extending the STEEP trend analysis checklist (Szpilko, 2020).

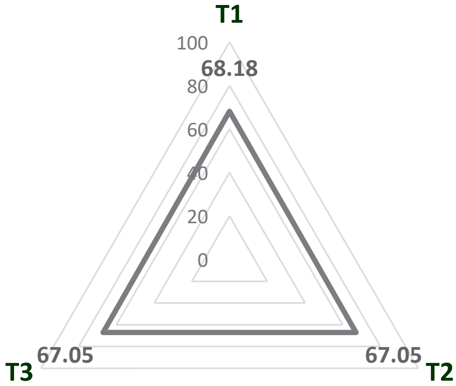
3. Research results

Three theses concerning Copernicus satellite communication received high relevance ratings based on indicators (Figure 1). Experts recognised the potential to empower end-users, promote sustainability, and enhance supply chain adaptive capacity during disruption, explaining the high ratings.

The factors enabling implementation of the theses differed slightly (Figure 2). For T1, "Increasing scope and quality of end-user education" was most important, potentially increasing independence from external providers and enabling faster, more flexible responses during disruptions. For T2, "Widespread promotion of the Copernicus programme" was key to facilitating informed decisions and sustainable supply chains. For T3, "Mutual and effective collaboration between key stakeholders of the Copernicus programme" was critical since successful optimisation relies on coordination between supply chain actors and Copernicus stakeholders.

Figure 3 shows the barrier indicators for each thesis. The main barrier for T1 was the "High level of uncertainty in data from citizen measurement networks", requiring improved reliability, stakeholder trust, collaboration, standardisation, and uncertainty management methodologies. For Thesis 2 and 3, "Low competences of end users of the Copernicus programme" was the top barrier, hindering data assessment, emergency decision-making, and environmentally friendly optimisation. Overcoming this, requires enhanced educational capacity through training, workshops, and knowledge sharing.

Experts identified the greatest theses impact on "Improving reliability, frequency, and flexibility of supply" (Figure 4). This suggests that Copernicus data analysis helps optimise operations in the supply chain by minimising environmental impact and mitigating socio-economic disruption delays and uncertainties.



T1. *The market for free applications utilizing Copernicus data will experience rapid growth, leading to an expansion in independent satellite data analysis by end-users*

T2. *Copernicus data, when subjected to multidimensional analysis, will facilitate environmentally conscious supply chain management through the provision of secure transportation, eco-friendly transportation options, and meteorological forecasts for transportation purposes*

T3. *During times of socio-political crises such as wars, migration, and economic downturns, the significance of Copernicus data analytics will rise, offering opportunities for optimizing supply chains.*

Fig. 1. Values of relevance indicators for theses on satellite communications

Source: (Ejdys et al., 2023).

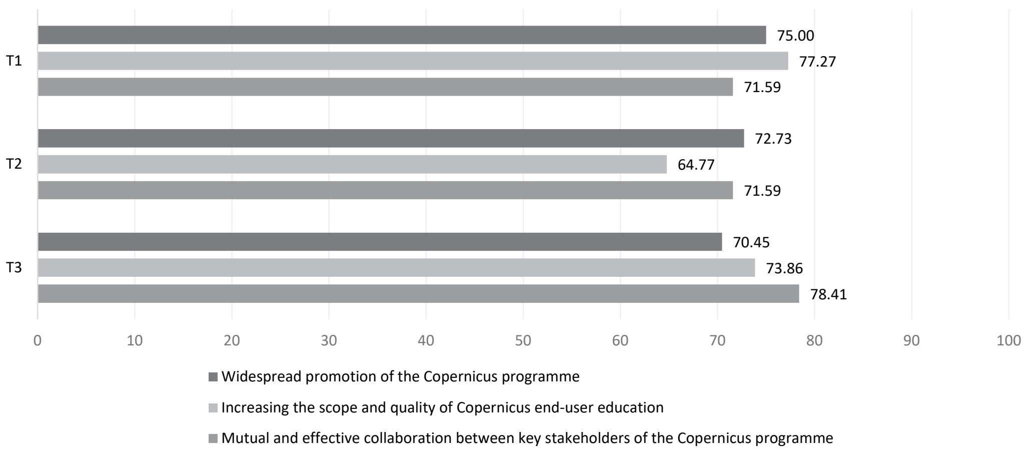


Fig. 2. Values of indicators relating to the drivers of the Delphi thesis

Source: (Ejdys et al., 2023).

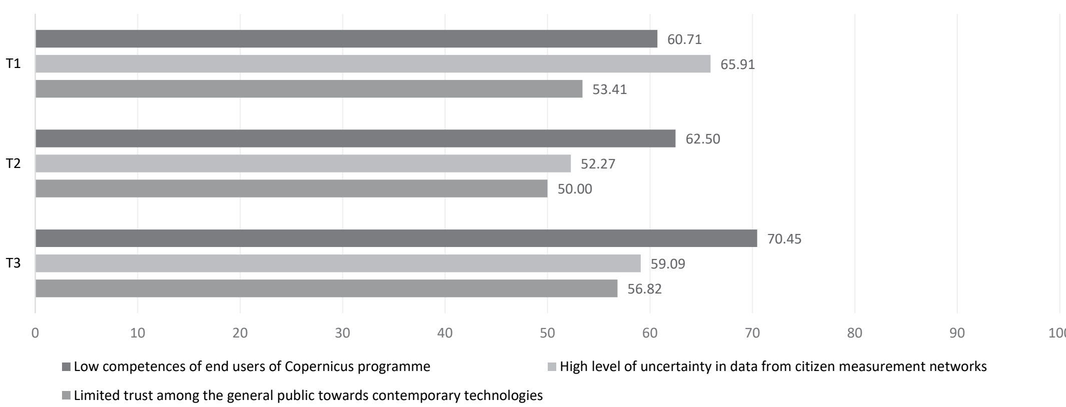


Fig. 3. Values of indicators relating to barriers to the Delphi theses

Source: (Ejdys et al., 2023).

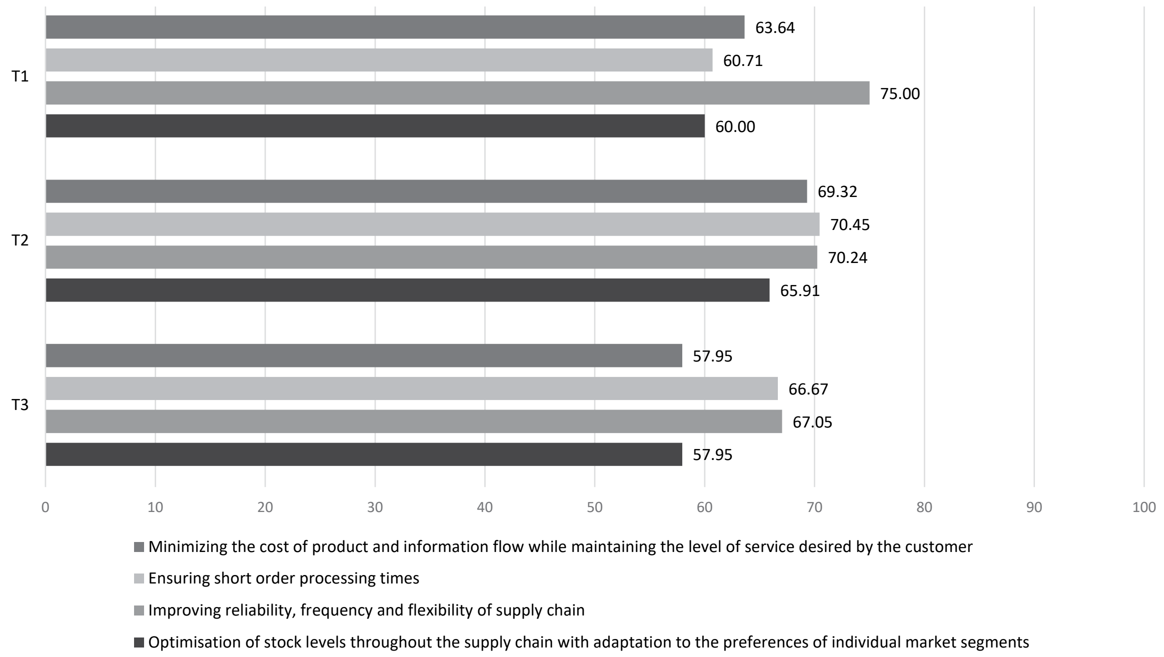


Fig. 4. Values of theses strength indicators for supply chain functions

Source: (Ejdys et al., 2023).

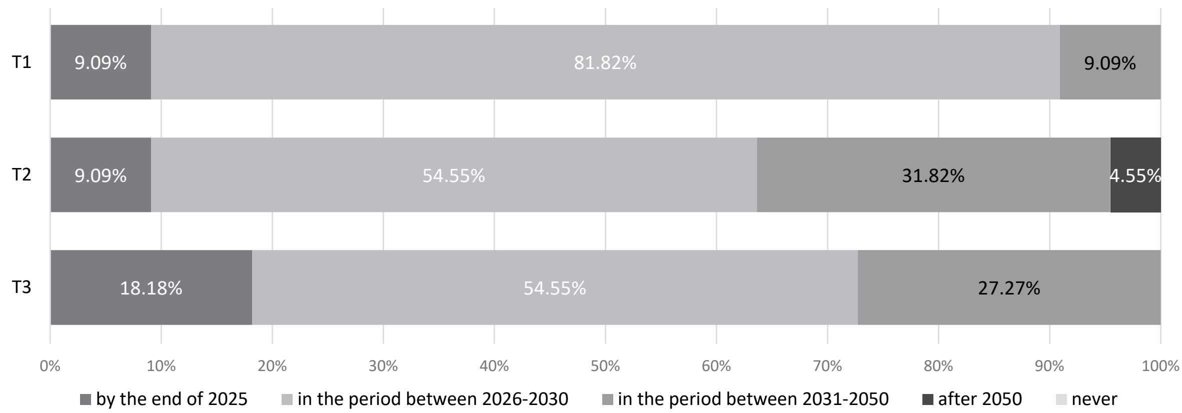


Fig. 5. Time perspective for the implementation of the individual theses

Source: (Ejdys et al., 2023).

Figure 5 shows the time horizon assessments for each thesis. Importantly, none of the theses were considered impossible. Experts recognised that even uncertain, distant theses could potentially materialise in various future possibilities.

The study identified 14 factors through STEEPED analysis (Table 1). Experts rated the importance and uncertainty of these factors on a seven-point scale (Figure 6). Factors with the highest importance and uncertainty in the STEEPED context were environmental and political (Figure 7). Managing these requires monitoring, adapting to changing standards, and collaborating with stakeholders for long-term supply chain resilience and sustainability. For example, factor P1 suggests anticipating and mitigating geopolitical uncertainty risks, continuous monitoring, scenario planning, and adapting strategies. Environmental or political disruptions in one region can cascade across the entire supply chain. Copernicus-enabled supply chain resilience relies on identifying vulnerabilities and addressing them across stages and locations for stability.

The Delphi survey included an open-ended question on possible actions to build EU satellite com-

Tab. 1. STEEPED factors that can foster the resilience of supply chains in the area of satellite communications in the European Union

STEEPED index	Name of the factor
Societal1 **S1**	• Standard of living and safety of individuals in society
Societal2 **S2**	• Public confidence in contemporary technologies
Technological1 **Th1**	• Advancement in Artificial Intelligence
Technological2 **Th2**	• Progress in Internet of Things systems
Economic1 **Ec1**	• Proficiency of end-users utilising Copernicus data and services
Economic2 **Ec2**	• Collaboration among key stakeholders involved in the Copernicus programme
Environmental1 **En1**	• The extent of climate neutrality and biodiversity preservation
Environmental2 **En2**	• Utilisation of natural resources through modern digital technologies, such as measurement, control, monitoring, and reporting
Politycal1 **P1**	• The stability of geopolitical conditions
Politycal2 **P2**	• The effectiveness of legislation regarding cybersecurity and digital data use
Ethical1 **Et1**	• Willingness to embrace technological innovations that enhance quality of life, including reducing environmental pollution
Ethical2 **Et2**	• The involvement and contribution of civil society
Demographic1 **D1**	• Challenges posed by aging population
Demographic2 **D2**	• The scale of international migration

Source: (Ejdys et al., 2023).

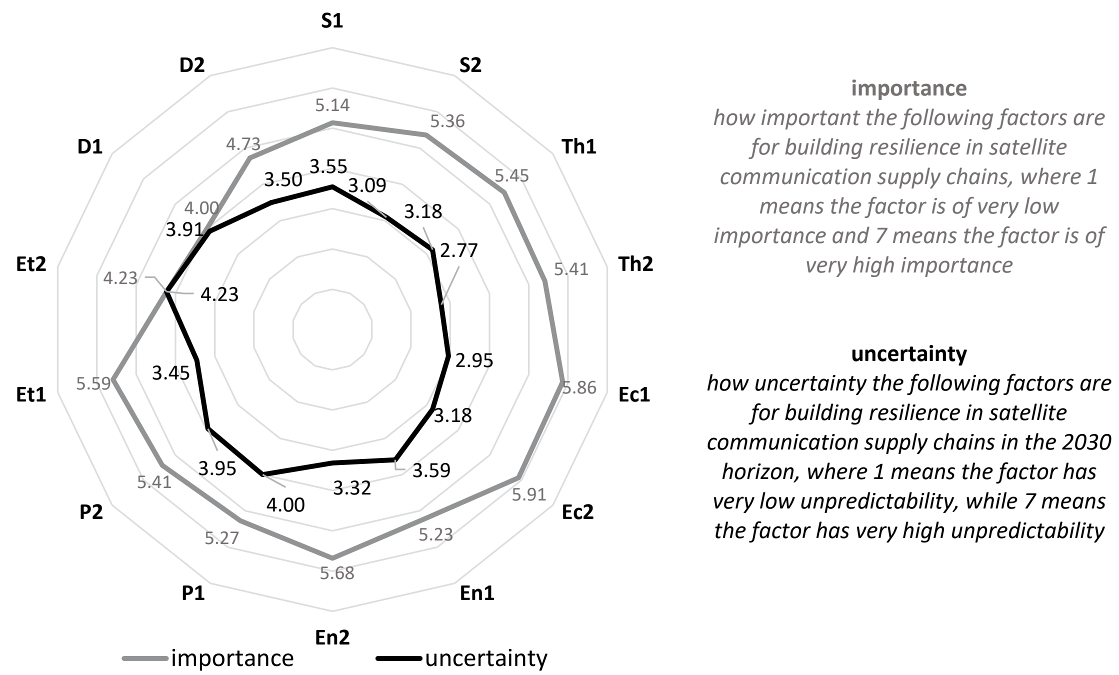


Fig. 6. Seven-point-scale rating of the importance and uncertainty of the following factors for building resilience in satellite communication supply chains

Source: (Ejdys et al., 2023).

munications supply chain resilience. Experts suggested ensuring secure, autonomous, accessible communication services; better critical technology supply chain control; open Copernicus data; synchronising Copernicus with relevant EU programmes like Horizon Europe and Digital Europe; and bridging the gap between satellite data and decision-making.

Each option has proposed strategic actions to enhance the effectiveness of the Copernicus programme. Strategic Option 1 focuses on supporting relevant EU management institutions. Key actions include optimising European supply chains by prioritising the Copernicus satellite programme as a vital Earth observation resource. This prioritisation is

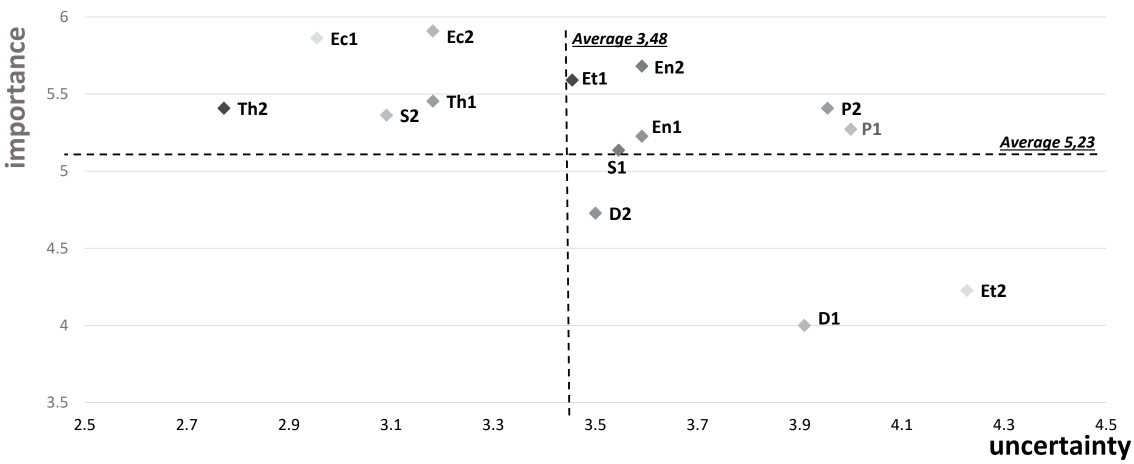


Fig. 7. Importance and uncertainty of STEEPED factors

Source: (Ejdys et al., 2023).

critical for EU policy formulation and European Data Spaces, aligning with relevant EU framework programmes. Promoting supply chain management within EU countries, especially semiconductor manufacturers and Copernicus data providers, is also crucial. Legislation ensuring economic independence from non-EU technologies must be enacted. Bridging the gap between Copernicus data and decision-making necessitates establishing a transparent control mechanism for raw material purchases and critical technology-related supply chains. Measures to safeguard satellites from hostile hacking attacks are imperative, ensuring full EU control and operation, along with the development of new satellites enabling direct servicing and repair in space.

Strategic Option 2 focuses on supporting Copernicus users. Creating incentives like concessions, grants, and support forms is vital to encourage Copernicus data and service usage, particularly in building resilient supply chains. It is essential to use case studies to identify effective and ineffective practices in building resilient supply chains. These lessons should be shared openly, contextualising them within specific crisis impacts for supply chain optimisation. Collaboration with the Copernicus User Dissemination Framework Partnership Agreement (FPCUP) consortium for projects enhancing supply chain resilience is valuable. A promotional campaign is necessary to emphasise the advantages of using Copernicus' free data for supply chain strengthening. Educational efforts should focus on acquiring interdisciplinary competencies for effectively analysing Copernicus-derived data. These strategic actions empower stakeholders to make informed decisions, reinforcing supply chain operations against disruptions and ensuring resilience and sustainability.

4. Discussion of the results

The authors identified opportunities and threats related to the strategic options, considering current trends and megatrends. Strategic Option 1, which supports EU institutions managing Copernicus, includes opportunities like providing citizens and businesses secure Copernicus-based information, systems, services and applications, especially for cybersecurity (Kaur & Ramkumar, 2022). Precise monitoring enabling accurate agricultural and environmental management combined with the Internet of Things development (Doshi et al., 2019) is another opportunity. Strengthening EU education systems through improved multidimensional data analysis competencies is also an opportunity, although with risks like training costs, technology expenses, prohibiting existing agricultural practices based on new geospatial data, and a shortage of data science teaching staff.

For Strategic Option 2, which supports Copernicus users, opportunities include increasing accessibility for citizens to secure Copernicus-based systems, services and applications. Recognising the growing importance of citizen scientists (Roche et al., 2020) and empowering end-users to predict natural phenomena and rationalise agricultural production are also opportunities, as is promoting scientific and business cooperation to advance Copernicus. However, threats include potential digital exclusion of groups like the Silver Generation (Butt & Draheim, 2021), ensuring cybersecurity of Copernicus-based information, systems and applications potentially incurring costs, uncontrolled in-situ facilities causing environmental interference, and users making decisions based on falsified data from hacking (Lukin & Haselberger, 2020). Concerns have also been raised about unfavourable crop regulation changes negatively impacting farmers.

Promoting Copernicus and its data in economic sectors can ensure a reliable resource supply. An example is the RawMatCop project, securing mineral supply. Implementing Copernicus EU-wide enhances digital capabilities, aiding workforce preparation for digital transformation (Kasmaeeyazdi et al., 2021).

Conclusions

Recent events in European socio-economics highlight the need to evaluate supply chain risks and resilience of Copernicus satellite communications. This study proposes two strategies to enhance resilience and mitigate disruptions. The first strategy supports EU institutions managing the Copernicus programme, while the second assists users and intermediaries associated with the programme.

The study used Delphi, a literature review, and the STEEPED analysis to examine theses on satellite communications. Experts expect rapid growth in the free apps market utilising Copernicus data, enabling end-users to independently analyse satellite data. They foresee satellite communications supply chains transforming into ecosystems that integrate value-added activities between 2026–2030.

Two enabling factors were identified: (1) enhancing Copernicus end-user education and (2) promoting mutual collaboration between key stakeholders. First, by enhancing Copernicus end-user education, individuals and organisations can acquire the necessary knowledge and skills to effectively utilise and analyse Copernicus data. This will contribute to the growth of the market for free applications based on Copernicus data, as pointed out in thesis T1. Second, mutual and effective collaboration among key stakeholders of Copernicus, including researchers, entrepreneurs, and politicians, can foster innovation, knowledge sharing, and coordinated efforts towards leveraging Copernicus data for supply chain optimisation, environmental management, and decision-making during crises. This collaboration aligns with the multidimensional analysis of Copernicus data mentioned in T2 and the importance of Copernicus data analytics during socio-political crises brought up in T3.

The study identified two key barriers: (1) low end-user competences hindering market growth and (2) high uncertainty in data from citizen measurement networks impacting multidimensional analysis. These barriers affect data reliability and limit potential uses of Copernicus data. For the T1, rapid app market growth depends on the end-user ability to effectively analyse and use the data. If end-users lack the necessary skills, independent analysis could be limited. For the T2, multidimensional analysis of Copernicus data is important for environmentally conscious supply chain management. However, high uncertainty in data from citizen measurement networks can introduce inaccuracies, potentially limiting analysis reliability and effectiveness. This could create challenges in using Copernicus data for secure, eco-friendly transportation and accurate forecasts. For the T3, during socio-political crises, the value of Copernicus data analytics in optimising supply chains increases. However, the low skills of end-users can restrict effective utilisation during complex, volatile situations. Additionally, high uncertainty in citizen measurement data can add further difficulties, potentially impacting analytics accuracy and reliability during crises.

The study also analysed the impact of the theses on supply chain functions, emphasising improvements in reliability, frequency, and flexibility of delivery. Additionally, based on STEEPED analysis, 14 factors were recognised, including civil society involvement, cybersecurity legislation, ageing population, and geopolitical stability. Among these factors, the stability of geopolitical conditions emerged as the most important and simultaneously the most uncertain aspect of the study.

Despite the potential domains for Copernicus programme activities, challenges arise from geographical dispersion, diverse user communities, and varying preferences (Taramelli et al., 2019). Managing different initiatives becomes difficult but poses a significant challenge requiring dedicated scientific efforts.

Moreover, technical issues identified by the Delphi study and the work of the European Innovation Council (European Innovation Council (EIC) Work

Programme 2023, 2023) include a growing number of dysfunctional satellites, limited in-space servicing capability, and EU's limitations in controlling and maintaining Copernicus infrastructure. These concerns necessitate the analysis of the strategic autonomy of EU space assets.

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DETERMINING A FUZZY MODEL OF TIME BUFFER SIZE IN CRITICAL CHAIN PROJECT MANAGEMENT

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ABSTRACT
Elaborating and applying a new model for estimating the time buffer size of a project programme, which shall guarantee a 90 % probability of timely project execution. The research included source text analysis to provide information on a research gap and the identification of the research problem. The research problem was identified: the time buffer size in a critical path programme does not guarantee a 90 % probability of timely project execution. A new model was then elaborated to estimate the buffer size; it was applied in a technical production preparation project. An additional comparative analysis was performed using the following methods to verify the model more accurately: half of the time total of a path, the sum of squares (SSQ), and the root square error method (RSEM). The application of the fuzzy model to estimate the buffer size in a critical chain programme offers can shorten the total planned project duration. It has a higher probability of timely project execution than other methods for estimating the buffer size. It guarantees a 90 % probability of timely project execution, keeping aggressive task times, which eliminates unwanted situations such as student syndrome, Parkinson's law, overestimating task duration, and multitasking. Project programming is an inherent part of the project planning stage in project management. Recently, project management has been increasingly developing, which has been confirmed by the article's source literature analysis. The analysis revealed a research gap in models estimating project buffer size, which might guarantee a 90 % probability of timely project execution. Thus, a fuzzy model for estimating time buffer size in a critical chain was developed, constituting added value to the science of management and quality of production engineering (currently, mechanical engineering). The fuzzy model for estimating time buffer size was applied in one Polish enterprise in a project for a new product's technical production preparation. The fuzzy model for estimating time buffer size permits the shortening of the duration of tasks to aggressive times, guaranteeing a 90 % probability of project timely execution. The elaborated model for estimating time buffer size may be applied further in practice in projects programmed using the critical chain method.

KEY WORDS
project management, project scheduling, critical chain project management, time buffer, buffer size, fuzzy sets

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INTRODUCTION

Project scheduling is a standard activity of every business unit that applies the project approach in its activity management. Research of the past quarter of the century shows that success depends on many factors. In the 1960s and 1980s, project success was measured by cost, time, and scope, also known as the iron triangle of project management (Atkinson, 1999). Over time, new project success factors have emerged, e.g., the satisfaction of key stakeholders, including the project team and sponsors (Jugdev

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& Müller, 2005; Shenhar et al., 2001; Serrador & Turner, 2014; Turner & Zolina, 2012; Young & Poon, 2013), competences of the project team, achieving strategic goals, appropriate communication (Cserháti & Szabó, 2014; PMI, 2013), using methodologies, methods, and techniques supporting project management, risk management, optimisation end clearly defined business goal (Hass, 2010; Müller & Turner, 2007, The Standish Group, 2013; Sebestyen, 2017; Martens et al., 2018). Critical success factors (CSF) vary depending on the industry in which projects are being implemented (Spalek, 2014; Urbański et al., 2019). However, regardless of the industry, there are common factors that can be identified:

- defining appropriate project aims, resources, and parameters,
- supporting and engaging management staff,
- maintaining project stakeholder relations and informing them of progress in project execution,
- ensuring competencies of managers and project team members,
- establishing project schedule and programme well; properly distributing tasks and duties within a project,
- regularly monitoring and inspecting project risks,
- solving the most important issues at the highest management level,
- optimising the project, i.e., dividing the project into smaller projects,
- using appropriate methodology, project management methodologies or techniques,
- clearly identifying the project aim.

As project success is influenced by the application of an appropriate methodology, an attempt has been made to use an innovative critical chain project management approach, CCPM, developed by Goldratt for the technical project programming for developing a new product's production. The research focused on a method for determining the buffer size of project time.

Critical chain project management constitutes a novel method that reduces the duration of individual tasks, decreases the project execution cost and achieves the determined goal. The method's author assumes that a project manager should go through the following stages (Goldratt, 1997; Leach, 2014) when scheduling a project:

- determining the project's scope, meeting a specified cost and the shortest possible time,
- identifying the critical chain,
- limiting task duration within the critical chain,
- introducing buffers protecting the critical chain,
- determining buffer size,
- monitoring project execution and taking corrective measures.

The project manager estimates the duration of tasks and assumes a safety margin to obtain a guarantee for timely project execution. Goldratt claims that the CCPM method is necessary to reduce the time to aggressive estimations (t0.5), which gives about 50 % certainty of timely task execution, and to introduce time buffers. According to Leach (2005), a buffer is "a process surplus, time span or budget assigned, applied for protecting the flow planned, delivery time or estimating cost in a production process or a project". Two kinds of time buffers have been distinguished in the critical chain concept: project buffer (PB) and feeding buffer (FB) (Goldratt, 1997; Izmailov et al., 2016; Leach, 1999, 2014; Raz et al., 2003). A project buffer placed at the end of the critical chain to protect the project scheduling removes the student syndrome and secures timely project execution. The feeding buffer connects the noncritical path with the critical chain, protecting the critical chain from a delay on the noncritical path, which can delay project execution.

The project manager uses the CCPM method for project scheduling to determine the size of time buffers. Time buffer size in project scheduling has been frequently targeted by research over the recent years. The research detailed the following methods: a 50 % rule, the square root of the sum of squared differences for estimated time deviation, and the root square error method. Most of these methods outlined in the existing literature do not consider the significant critical chain method assumption, in which project scheduling, after accounting for time limiting and time buffers, must have at least a 90 % probability for timely project execution. Therefore, a research gap exists in the discipline of management and quality sciences, and production engineering. The article's authors attempted to solve the research problem: the size of the time buffers in the critical chain schedule does not provide a 90 % probability of project completion on time. The following research questions will be analysed to solve the research problem:

- What methods estimating the time buffer size have been described in the literature?
- Do the methods described in the source literature guarantee a 90 % probability of timely project execution?
- Can fuzzy numbers be used to determine the time buffer size? Why are they worth being applied?

- How can a 90 % probability of timely project execution be guaranteed?
- Will elaborating a fuzzy model for determining the time buffer size guarantee a 90 % probability of timely project execution?

Answers to the first two research questions were obtained after analysing the literature described in the Literature Review. Answers to the third and fourth research questions are presented in Research Methods, which describes the fuzzy model for estimating the time buffer size in a critical chain programme. The answer to the fifth research question is presented in Research Results and Discussion, which include a case of sample application of a fuzzy model in a project programme, including a new product's technical production preparation and a comparative analysis using other methods for estimating the time buffer size.

1. Literature review

During recent decades, the project planning approach under conditions of uncertainty has become increasingly more common, which gave rise to the search for new methods for the management of programme variability and instability in a research environment. One such method is widely analysed in the literature and includes a critical chain based on Goldratt's theory of constraints. If properly applied, it may reveal flexibility and robustness in project scheduling.

Initially, a review of literature trends in Scopus and Web of Science databases was performed, which showed that the term "critical chain" is growing more popular every year. Figs. 1 and 2 show the scheme created based on a graph generated in VOSviewer regarding the co-occurrence of the term "critical chain" with other terms. After optimisation, five clusters were obtained.

In the examined source query, with "minimum number of occurrences of a keyword" = 5, out of the 1291 keywords, 63 met the threshold. For each of the 63 keywords, the total strength of co-occurrence links with other keywords was calculated. The keywords with the greatest total link strength were selected.

Cluster 1, "Project management", created in VOSviewer, contains concepts related to the critical path method, critical chain project management,

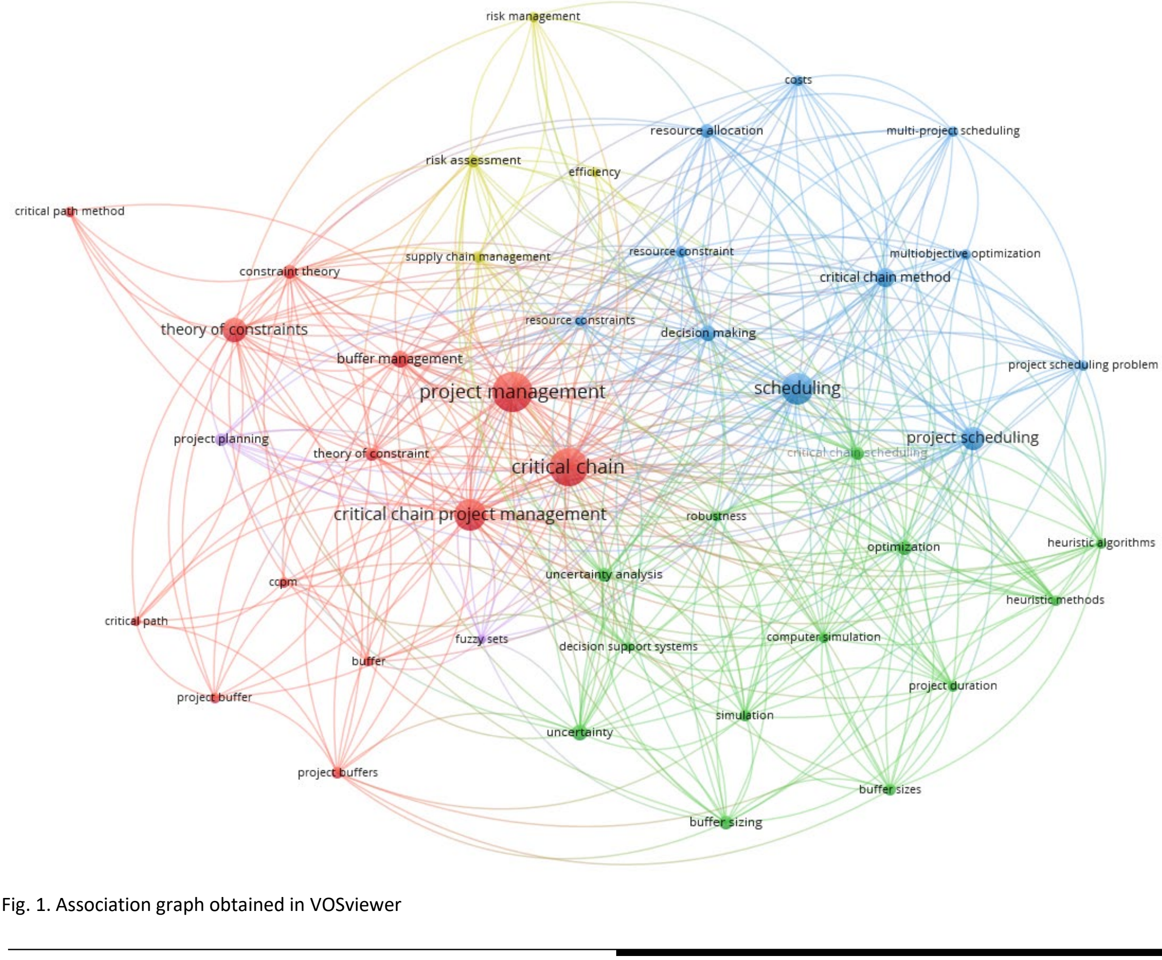

Fig. 1. Association graph obtained in VOSviewer

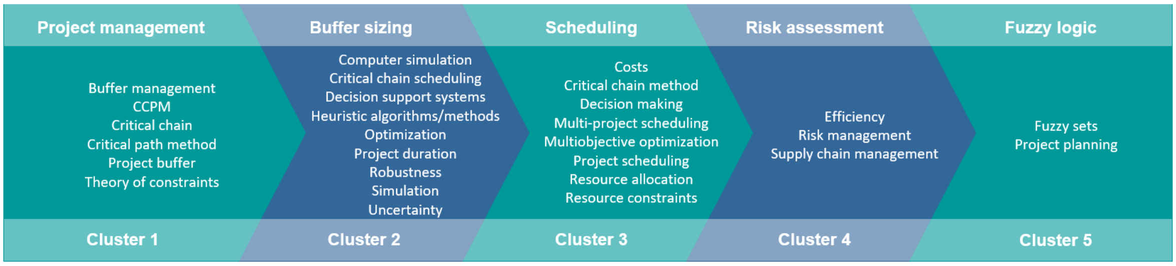

Fig. 2. Clusters obtained in VOSviewer

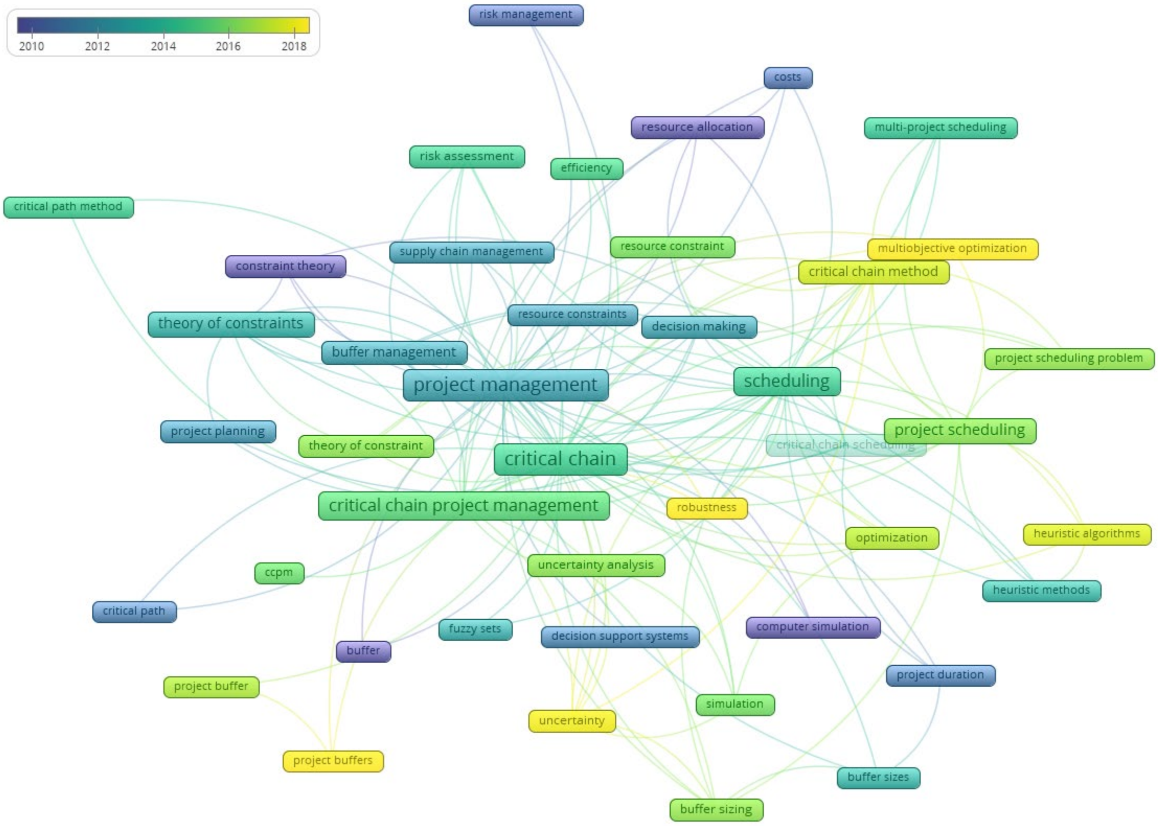

Fig. 3. Association graph with min. strength=3 obtained in VOSviewer

buffer management, and the theory of constraints. It includes issues related to project management, the operation of which is largely based on the previously mentioned concepts. Cluster 2, "Buffer sizing", is a group of concepts related to methods, techniques and tools supporting modelling and decision-making in operational project management, including buffer size estimation. In this cluster, the keywords "buffer sizing" and "buffer sizes" are linked with all other groups, which indicates the presentation of the studied concepts from the perspective of different approaches or analysed problems, such as: "computer simulation", "critical chain scheduling", "decision support systems", "heuristic algorithms/methods", "optimization", "project duration", "robustness", "simulation", "uncertainty". Terms in Cluster 3, "Scheduling", relate to project scheduling problems. This group has the term "critical chain method" with a total link strength of 84, which means that the context of research in this area is wide. Cluster 4, "Risk assessment", brings together concepts relating to risk management processes and their efficiency. Cluster 5, "Fuzzy logic", has only two concepts: "fuzzy sets" and "project planning", and it is a niche area of research in this source query.

The association graph presented in Fig. 3 indicates a successive development of issues related to a critical chain over several decades. The analysis was

Tab. 1. List of contemporary methods for estimating the time buffer size

Author	Year	Method assumptions
Goldratt E. M.	1997	Goldratt's 50 % rule is the simplest buffer estimation method. Buffer size constitutes half of the tasks' time sum on a path.
Newbold R.	1998	The root square error method (RSEM) extended Goldratt's concept by using the normal distribution. Buffers constitute risk aggregation in a project, and therefore, the uncertainty indices are used to calculate the buffer size.
Leach L. P.	2003	The sum of squares (SSQ) method assumes that the difference between the estimated optimistic and pessimistic duration constitutes a multiplication of standard deviation. This method uses the square root of the sum of squared differences for the estimated time deviation in calculating buffer sizes. The method differs from RSEM by the value of standard deviation.
Herroelen W. & Leus R.	2004	A method for calculating time buffer size in terms of solving the expected scheduling instability using cost minimisation task.
Van de Vonder S., Demeulemesser E., Herroelen W. & Leus R.	2005	
Tukel O. I., Rom W. O. & Eksioglu S. D.	2006	The adaptive procedure with density (APD) and the adaptive procedure with resource tightness (APRT) methods agree with the square root method assumptions for calculating time buffer size. The approach is extended by introducing a new coefficient.
Ashtiani B., Jalali G-R., Aryanezhad M-B. & Makui A. A.	2007	Ashtiani's root square error method (ARSEM) proposed a new method of buffer size calculation based on the RSEM method. This method is based on connecting the normal disintegration with the analysis of project risk parameters.
Tenera A. B.	2008	Monte Carlo simulation techniques are used for calculating the buffer size, which have been enriched by the ultimate deadline of the critical chain exceeding risk analysis.
Min Z. & Rongqiu C.	2008	Min's fuzzy approach buffer sizing technique with the fuzzy approach applied as a support tool in the planning process. The buffer size is determined based on the β index and the project risk level.
Shi Q. & Gong T.	2010	An improved method for determining the buffer size to overcome the resource constraints and deal with fuzzy uncertainties in project management. The method integrates three uncertainties, i.e., resource sharing, the complexity of the network and project managers' preference risk, to optimise the buffer configuration.
Fallah M., Ashitiani B. & Aryanezhad B.	2010	Log normal distribution applied in project buffer size calculation extended the approach of determining the time buffer size by introducing the uncertainty index.
Liu J. & Whangbo T-K.	2012	Statistical analysis in determining the time buffer size.
Slusarczyk A., Kuchta D., Verhulst P., Huyghe W., Lauryssen K. & Debal T.	2013	RISK CLASS ASSESSMENT (RCA) proposes determining the buffer size according to risk classes. The risk size is determined based on the level of risk, i.e., low, average, and high values.
Zhang J., Song X. & Díaz E	2014	Optimisation attributes are applied to calculate the time buffer size by applying the Monte Carlo method.
Kuchta D.	2014	The expert method is applied in determining project buffer size. Expert opinions have been expressed on the limits of buffer size and planned project completion.
Iranmanesh H., Mansourian F. & Kouchaki S.	2015	Density coefficients and risk aspects are used for calculating the time buffer size.
Poshdar M., González V., Raftery G., Orozco F., Romeo J. & Forcael E.	2016	Probabilistic method of buffer allocation (PBAL), which facilitates the final decision on the buffer size to be taken by project planners, based on their preferences concerning project completion time.
Zhang J., Song X. & Díaz E.	2016	A method for determining the buffer size based on complex resource tightness so as to better reflect the relations between activities and improve the accuracy of determining project buffers.
Taher S. F. & El-Korany T. M.	2016	The blue method estimates the buffer size according to probability and activity duration and is based on the distribution of variables. A, b, and m are described as optimistic, pessimistic, and the most probable activity duration, respectively.

Ghoddousi P., Ansari R. & Makui A.	2017	A multi-measure method for calculating the time buffer size considers path complexity, flexibility criteria, criticality index, and resistance measure. It facilitates the economic aspects of project buffers, i.e., the impact of external and internal risk factors on buffer size.
Roghanian E., Alipour M. & Rezaei M.	2018	A square root sum method modified using uncertainty indices.
Zohrehvandi S. & Khalilzadeh M.	2019	Hybrid approach applied in calculating time buffer size, connecting FMEA and APPT (resources saving methods).
Zarghami S. A., Gunawan I., Corral de Zubielqui G. & Baroudi B.	2020	A new method for determining the size of the project buffer for CCPM by developing a probabilistic measure obtained through a reliability analysis of project resources. In this method, buffer size was determined by assigning a scaling factor to the standard deviation of a chain.
She B., Chen B. & Hall N. G.	2021	A procedure for buffer sizing based on network decomposition. First, the size of a feeding buffer is determined from all associated noncritical chains. Second, the project buffer incorporates safety margins outside the critical chain by comparing feeding chains with their parallel critical counterparts.
Li H., Cao Y., Lin Q. & Zhu H.	2022	Full-factor design of experiments and Monte Carlo simulation used to construct the required dataset. Support vector regression is adopted to train the project buffer prediction model.

Source: Elaborated by the author based on (Ashtiani et al., 2007; Fallah et al., 2010; Ghoddousi et al., 2017; Goldratt, 1997; Herroelen & Leus, 2004; Liu & Whangbo, 2012; Iranmanesh et al., 2015; Kuchta, 2014; Leach, 2003; Li et al., 2022; Min & Rongqiu, 2008; Newbold, 1998; Poshdar et al., 2016; Roghanian et al., 2018; She et al., 2021; Shi & Gong, 2010; Slusarczyk et al., 2013; Taher & El-Korany, 2016; Tenera, 2008; Tukel et al., 2006; Van de Vonder et al., 2005; Zarghami et al., 2020; Zhang et al., 2014, 2016; Zohrehvandi & Khalilzadeh, 2019).

narrowed to "min. strength" = 3 that determines, respectively, the minimum strength of links displayed in the visualisation.

The new (within one source query no sooner than after 2016) unrelated or weakly related terms include "project buffer", "buffer sizing", "uncertainty", "robustness", "project scheduling", "optimization", "heuristic algorithms", which may prove a research gap in project programming phenomenon, applying CCPM and a need to focus on determining the buffer size, considering the uncertainty conditions and robust scheduling problems.

The study showed a strong correlation between the terms "critical chain" and "project management", "scheduling", "theory of constraints", "buffer management", and "uncertainty". A noteworthy aspect is the increasing occurrence of phrases "robustness" and "optimization" concerning project scheduling, which indicates that these issues are gaining importance not only in the context of task scheduling in the production system but are increasingly used in project management. Robustness is a measure of the result after the application of a procedure under uncertainties or after the appearance of uncertainty, e.g., relative to the operation duration of the task, the availability of the resource, etc. The robustness of a schedule is, therefore, a way to characterise its performance. The method for determining the buffer size can be important for obtaining the right flexibility and robustness in project scheduling.

The literature survey showed a frequent occurrence of the critical chain topic with the terms "project duration", "decision-making", and "resource allocation". These dependencies may indicate the need to develop new heuristic methods to support decision-making in this area, as well as the importance of meeting the project deadline under conditions of uncertainty. In connection with these issues, the use of fuzzy logic gives promising results, but it is still a niche area of research.

Pursuant to the critical chain method, the determination of buffer size is an inherent element in project scheduling. The literature on the issue includes numerous methods for determining the buffer size. Some are very simple, and others require advanced statistical and mathematical methods. Table 1 presents an analysis of actual methods for estimating the time buffer size.

As outlined in the table and indicated by Zohrehvandi and Soltani (2022), buffer size in critical chain scheduling has been a subject of research for several years. Most researchers focused on modifying the most popular methods for calculating the time buffer size, such as the 50 % rule, SSQ, etc. Apart from modified previously established methods, several individual methods can be found in the existing literature on estimating the time buffer size, e.g., RSE, APD, APRT, MIN'S FUZZY, or BLUE. Also, attempts were made to determine the most efficient method, e.g., by Altarazi and Bao (2015) and Moussa, El-Korany, Etman, and Tahir (2016). Results indicate that methods such as the 50 % rule, SSQ and RSEM are more efficient in estimating the time buffer size when the task character is known, while in other cases, it is better to apply methods based on simulations.

The premises above and the fact that not all methods for evaluating the buffer size consider the project execution probability at a level of at least 90 % provided the basis for a new model developed and described in this paper. The application of fuzzy numbers and normal distribution factors may constitute a suitable model for buffer size and is further explored in this paper.

2. Research methods

The analysed research problem focuses on the method for determining the project buffer size, which would guarantee a 90 % probability of timely project execution, also under uncertainty conditions and robust scheduling problems.

Project scheduling methods are frequently based on network models, which assume a certain precedence relation of particular jobs/processes. Precedence relations, employed to model technological and organisational relations between jobs, are established at the model-building phase and result from the technology and limitations in the scope of realised jobs or specified resource allocation. The given type of schedule assumes no variables and is, therefore, modelled using deterministic analysis networks (DAN) of a determined logical structure.

Performance determinant factors of a project can be represented by the one-node network. The precedence relation between production jobs can be modelled using a connected directed acyclic unigraph $G=\langle V, E\rangle$ with one start and end node, where $V=\{1, 2, K, n\}$ denotes the set of project tasks (in the network described as an activity), and $E\subset V\times V$ is a binary relation determining the precedence relation between activities.

The fuzzy model for estimating the project time buffer includes the application of two elements. First, triangular fuzzy numbers are to be applied to estimate the time buffer size with different project completion probabilities. It was determined that *B'* is a time buffer fuzzy number (project or feed) with the following definition: $B_i' = \left(\overline{b_\iota},\ \overline{\overline{b_\iota}},\ \widetilde{b_\iota}\right), \bar{b} < \bar{\bar{b}} < \breve{b}$, where $\bar{\bar{b}}$ is the buffer size at which the project has a 90 % probability of timely execution, and the parameter $\bar{b}$ defines the buffer size at an 85 % probability, and $\tilde{b}$ at a 95 % probability of timely project execution.

Second, fuzzy number sets are selected according to the probability of project execution based on the normal distribution factor (Nafkha, 2016; Ravalji & Deshpande, 2014):

$$x = \frac{T_d - T_e}{\delta_c}, \tag{1}$$

where: x is the time scaled to N [0,1], T_e is the planned project execution time, estimated according to CCPM, T_d is the project execution time, resulting from previous scheduling ($t_{0.9}$), and δ_c is the standard deviation. Due to the fact that time T_e is a sum of aggressive times (T_e') and buffer size (*B*), formula (1) was transformed as follows to determine the triangular fuzzy numbers:

$$B = T_d - x\delta_c - T_e' \tag{2}$$

The assignment function of the analysed model defines time buffer size with a determined probability of timely project execution. The assignment function formula is as follows (Molinari, 2016; Wang, 2015):

$$\mu(B') = \begin{cases} 0 & dla \quad B' \le \bar{b} \\ \dfrac{B' - \bar{b}}{\bar{\bar{b}} - \bar{b}} & dla \quad \bar{b} < B' < \bar{\bar{b}} \\ \dfrac{\tilde{b} - B'}{\tilde{b} - \bar{\bar{b}}} & dla \quad \bar{\bar{b}} < B' < \tilde{b} \\ 0 & dla \quad B' \ge \tilde{b} \end{cases} \tag{3}$$

Fuzzy sets conclusion has been assumed for the model according to the following formula:

$$\mu_{B_{i-1}\wedge B_i}(B') = \min\left(\mu_{B_{i-1}}(B'), \mu_{B_i}(B')\right) \tag{4}$$

Defuzzification is necessary to determine a number (as a time buffer value) to reflect the assumptions of the critical chain method and to meet the fuzzy model rule. It may be done using the following methods (Abbasbandy et al., 2004; Hellendoorn & Thomas, 1993; Saade & Diab, 2004; Pedrycz, 1993; Roychowdhury & Wang, 1996): first maximum, last maximum, middle maximum (middle of the best section), and the centre of gravity and height. This paper used the method of the "middle best sector" to calculate the time buffer size. First, it is necessary to find a section for which the assignment functions are at maximum. If there are several of them, the first one (the last and the longest) is selected. If there is no such section, the first peak value is assumed. If there is such a section, the middle

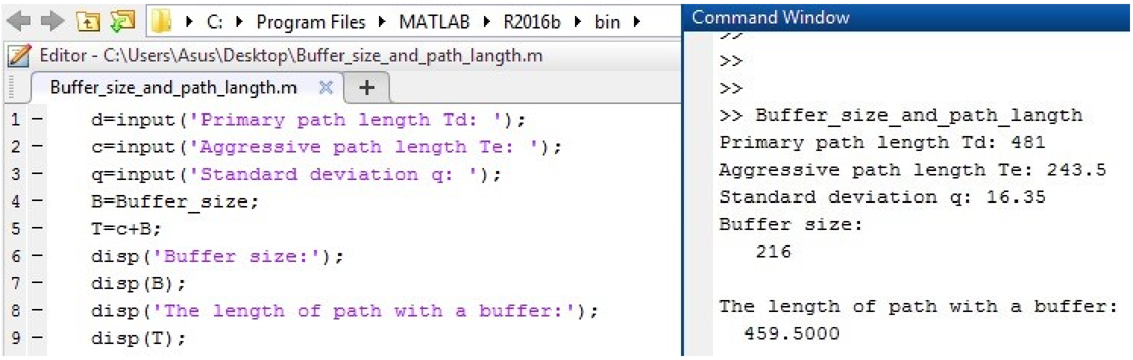

Fig. 4. Application of the project buffer size calculation developed in the MATLAB program

as the buffer size is assumed according to the formula: $z = a + b/2$, where a is the first maximum value of the membership function, and b is the second maximum value of the function.

As the described fuzzy model for estimating the buffer size requires that the project manager applies advanced mathematical tools, an application in MATLAB has been developed. The application determines the time buffer after adding the primary path length Td, the aggressive path length *Te*', and the standard deviation. Fig. 4 presents a view from the application developed in MATLAB.

3. Research results

The verification of the developed fuzzy model for estimating the time buffer size of a project has been carried out using technical preparation for a new product in one of the Polish enterprises as an example. Table 2 presents the project work structures.

The project consists of three stages and twenty-six tasks, and three milestones. Table 3 presents a listing of safe and aggressive duration times of individual tasks. Aggressive times were identified based on historical data and the use of the inverse of the cumulative normal distribution. The calculations assumed a probability of 50 %. Table 3 information also shows whether a task is critical and a milestone. Fig. 5 presents an example of a time buffer location in technical preparation production project scheduling. In this case, the critical chain consists of 22 tasks: 1, 2.1, 2.2, 4, 5.1, 5.3, 5.4, 5.5, 6.1, 6.2, 6.4, 6.5, 7.1, 7.4, 7.5, and 8. The project buffer (PB) has been put at the end of the path. There are also four noncritical paths, in which the task sequence is as follows: 3.2–3.3, 6.6, 6.7–6.8, and 7.2–7.3. Feed buffers FB1, FB2, FB3, and FB4 have been placed at the end of the noncritical paths.

After locating time buffers in scheduling, it is necessary to calculate their size. For this purpose, the application in MATLAB has been used. First, three triangular fuzzy numbers have been determined for the project buffer based on formula (2):

$$B'_{95\%} = (199.6; 210.6; 216.5),$$
$$B'_{90\%}(210.6; 216.5; 220.5),$$
$$B'_{85\%} = (216.5; 220.5; 223.7).$$

According to fuzzy logic, the buffer size for the example under consideration is 216 days with a standard deviation of 16.35. The standard deviation was calculated based on historical data. The estimated project time, according to the critical chain method, is 459.6 days and is 21.5 days shorter than in preliminary scheduling (about 4.5 % reduction). Unlike the method of half times sum on the path, fuzzy sets may not guarantee the shortening of the whole project by 25 %, but they do guarantee at least 90 % timely project execution.

An analogous procedure is applied for feed buffer size calculation. The first feed buffer has been identified after Task 3.3. Path 3.2–3.3 has been adopted for the calculation instead of path 3.1–3.3, as the first path is longer than the second. The first buffer size is 8.9 days, and the second buffer size is 11.5 days. The third corresponds to 11.5 days, while the fourth is 13 days. Following the CCPM method, the critical chain cannot change after the introduction of feed buffers into technical project preparation scheduling. This is witnessed in this procedure, and hence, the size of the buffers can be acknowledged as accurate.

Tab. 2. Project's work structure for the preparation of product production in the form of a list of functions

WBS	Name of stage/task
1	**Decision on project commencement**
2	**Market research**
2.1	Basic research
2.2	Applied research
3	**Economic analyses**
3.1	Project preliminary cost estimation
3.2	Product sale future income estimation
3.3	NPV index estimation
4	**Decision on product production preparation commencement**
5	**Structural preparation of new product production**
5.1	Construction assumptions development
5.2	New product preliminary design development
5.3	Technical design development
5.4	Prototype execution and testing
5.5	Execution design of construction development
6	**Technological preparation of a new product**
6.1	Technological plan concept development
6.2	Determining technological operations and their execution sequence
6.3	Selection of production machinery and equipment
6.4	Determining workshop support
6.5	Workshop special support structures development
6.6	Determining staff qualifications
6.7	Standards (quantities) of materials and standards of work time (operations)
6.8	Selection of technological process quality control
7	**Organisational preparation of new product production**
7.1	Production preparation
7.2	Determining supplies for new product production – resources and materials
7.3	Training – staff preparation for production
7.4	Market preparation for the production
7.5	New product promotion preparation
8	**Commencement of serial production**

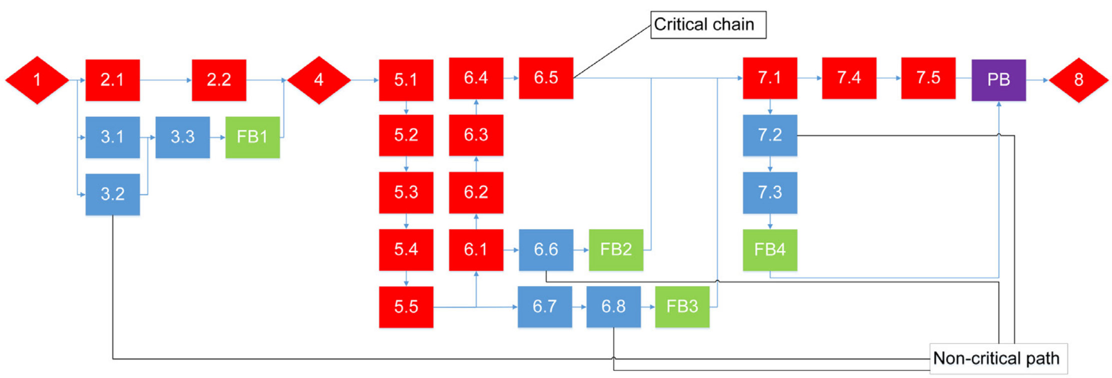

Fig. 5. Network of dependencies on the application of the critical chain method of production preparation

Tab. 3. List of task durations and relations between tasks

WBS	Predecessor	$T_{0.9}$ [days]	$T_{0.5}$ [days]	Critical task	Milestone
1		**0**	**0**	**Yes**	**Yes**
2		**89**	**45**	**Yes**	**No**
2.1	1	33	17	Yes	No
2.2	2.1	56	28	Yes	No
3		**24**	**12**	**No**	No
3.1	1	8	4	No	No
3.2	1	18	9	No	No
3.3	3.1;3.2	6	3	No	No
4	**2.2;3.3**	**1**	**0.5**	**Yes**	**Yes**
5		**182**	**92**	**Yes**	**No**
5.1	4	29	15	Yes	No
5.2	5.1	46	23	Yes	No
5.3	5.2	48	24	Yes	No
5.4	5.3	32	16	Yes	No
5.5	5.4	27	14	Yes	No
6		**103**	**53**	**Yes**	**No**
6.1	5.5	18	9	Yes	No
6.2	6.1	27	14	Yes	No
6.3	6.2	17	9	Yes	No
6.4	6.3	13	7	Yes	No
6.5	6.4	28	14	Yes	No
6.6	6.1	35	18	No	No
6.7	5.5	18	9	No	No
6.8	6.7	12	6	No	No
7		**106**	**53**	**Yes**	**No**
7.1	6.6;6.8;6.5	28	14	Yes	No
7.2	7.1	14	7	No	No
7.3	7.2	21	11	No	No
7.4	7.1	34	17	Yes	No
7.5	7.4	44	22	Yes	No
8	**7.3;7.5**	**0**	**0**	**Yes**	**Yes**

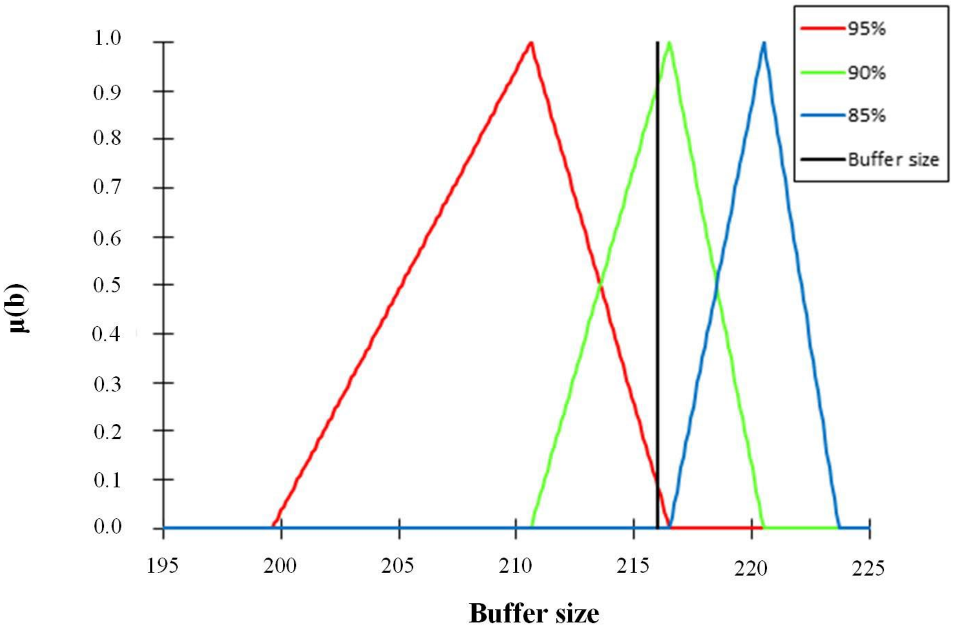

Fig. 6. Assignment function of triangular fuzzy numbers of project buffer size with defuzzification results

4. Discussion of the results

Table 4 presents a comparison of several methods selected for determining time buffer size to compare the proposed method with other methods described in the existing literature. The following methods have been selected for the research:

The half times sum at the aggressive scheduling path method. The buffer size is calculated using the following dependency (Ravalji & Deshpande, 2014):

$$Bufor = \frac{1}{2}\sum_{i=1}^{n} t_{0.5_i} \quad (5)$$

The method of square root of squared sum difference between safe time ($t_{0.9}$) and aggressive time ($t_{0.5}$). The dependency is presented in the following formula (Slusarczyk et al., 2013):

$$Bufor = \sqrt{\sum_{i=1}^{n}(t_{0.9_i} - t_{0.5_i})^2} \quad (6)$$

The root square error method (RESM) describes two square roots of the deviation sum between safe time and aggressive time. The buffer is calculated using the following formula (Ravalji & Deshpande, 2014):

$$Bufor = 2 * \sqrt{\sum_{i=1}^{n}\sigma^2} \quad (7)$$

Where:
σ — the difference between safe and aggressive time,
$t_{0,9}$ — estimated safe time and tasks,
$t_{0,5}$ — estimated aggressive time and tasks,
n — number of tasks in a path.

The listing presented in Table 4 indicates that the shortest planned project duration time (308.9 days) can be reached using the square root of the squared sum differences method between safe time ($t_{0.9}$) and aggressive time ($t_{0.5}$). The application of the method

Tab. 4. Listing of time buffer size determining methods

Buffer type	Path	Path length $T_{0.9}$ [days]	Path length $T_{0.5}$ [days]	Dependence	Buffer size [days]	Planned path time [days]	Change path time [days]	Change path time [%]
PB	1-2.1-2.2-4-5.1-5.2-5.3-5.4-5.5-6.1-6.2-6.3-6.4-6.5-7.1-7.4-7.5-8	481	243.5	(2)	216.0	459.5	-21.5	-4.5
				(5)	121.8	365.3	-115.7	-24.1
				(6)	65.4	308.9	-172.1	-35.8
				(7)	130.9	374.4	-106.6	-22.2
FB1	3.2-3.3	24.0	12.0	(2)	8.9	20.9	-3.1	-12.9
				(5)	6.0	18.0	-6.0	-25.0
				(6)	9.5	21.5	-2.5	-10.4
				(7)	19.0	31.0	+7.0	+29.2
FB2	6.6	35.0	18.0	(2)	11.5	29.5	-5.5	-15.7
				(5)	9.0	27.0	-8.0	-22.9
				(6)	17.0	35.0	-0.0	0,0
				(7)	34.0	52.0	+17.0	+48.6
FB3	6.7-6.8	30.0	15.0	(2)	11.5	26.5	-3.5	-11.7
				(5)	7.5	22.5	-7.5	-25.0
				(6)	10.8	25.8	-4.2	-14.0
				(7)	21.6	36.6	+6.6	+22.0
FB4	7.2-7.3	35.0	18.0	(2)	13.0	31.0	-4.0	-11.4
				(5)	9.0	27.0	-8.0	-22.9
				(6)	12.2	30.2	-4.8	-13.7
				(7)	24.4	42.4	+7.4	+21.1

Tab. 5. Buffer size, according to the probability of timely project execution

Probability	The value of the normal distribution function	Buffer size	Probability	The value of the normal distribution function	Buffer size
0.55	0.13	235.37	0.77	0.74	225.40
0.56	0.16	234.88	0.78	0.78	224.75
0.57	0.18	234.56	0.79	0.82	224.09
0.58	0.21	234.07	0.80	0.85	223.60
0.59	0.23	233.74	0.81	0.88	223.11
0.60	0.26	233.25	0.82	0.92	222.46
0.61	0.28	232.92	0.83	0.96	221.80
0.62	0.31	232.43	0.84	1.00	221.15
0.63	0.34	231.94	0.85	1.04	220.50
0.64	0.36	231.61	0.86	1.09	219.68
0.65	0.39	231.12	0.87	1.13	219.02
0.66	0.42	230.63	0.88	1.18	218.21
0.67	0.44	230.31	0.89	1.23	217.39
0.68	0.47	229.82	0.90	1.29	**216.41**
0.69	0.50	229.33	0.91	1.35	**215.43**
0.70	0.53	228.83	0.92	1.42	**214.28**
0.71	0.56	228.34	0.93	1.48	**213.30**
0.72	0.59	227.85	0.94	1.56	**211.99**
0.73	0.62	227.36	0.95	1.65	**210.52**
0.74	0.65	226.87	0.96	1.76	**208.72**
0.75	0.68	226.38	0.97	1.89	**206.60**
0.76	0.71	225.89	0.98	2.06	**203.82**

reduces the total project time by over 35 %, which may mean that such an optimistic determination of the buffer size can lead to reduced chances of timely project completion. A similar situation occurs with the 50 % rule method and the RSEM. Moreover, it should be considered whether the feed buffer sizes will change the critical chain flow. The analysis demonstrates that if the RSEM method is applied to determine the time buffer size, the critical chain will change, and hence, the method should be excluded in this case.

Analysis of the research results has been extended by checking whether the time buffer sizes determined according to these methods align with the main principle of CCPM, i.e., whether the project meets the minimum of a 90 % probability of timely project execution, following time reduction and introduction of buffers. To determine this, the project buffer size value is assessed using the normal distribution factor formula. Table 5 presents the calculation results.

This paper calculates that the project buffer should be between 203.82 and 216.41 days to meet the CCPM method requirements. The verification of whether the methods met the principle found only one such method, i.e., the project size estimating model, thereby substantiating the application of the model developed.

Research results prove that the model developed for estimating the time buffer size guarantees at least a 90 % probability of timely project execution. It is, therefore, necessary to rationally analyse the obtained buffer values and select a method that may guarantee at least a 90 % probability of timely project execution.

Conclusions

The presented research aimed at solving the following research issue: the time buffer size in the critical chain programme does not guarantee a 90 % probability of timely project execution. To solve the problem, the following research questions have been asked:

- What time buffer size estimation methods have been described in the literature?
- Do the methods described in the source literature guarantee a 90 % probability of timely project execution?
- Can fuzzy numbers be applied for determining time buffer size? Why are they worth applying?
- How can a 90 % probability of timely project execution be guaranteed?
- Will elaborating on a fuzzy model for determining the time buffer size guarantee a 90 % probability of timely project execution?

An answer to the first two research questions has been obtained from a source literature analysis, indicating that many methods are available for estimating the time buffer size; however, none of them guarantees a 90 % probability of timely execution. This encouraged the authors of this article to start searching for a new method for estimating the time buffer size. The analysis commenced from the rule that the total project execution time with time buffers must guarantee a 90 % probability of timely project execution. As projects are executed under uncertainty conditions and values for buffer size estimation are frequently inaccurate, it was proposed to apply triangular fuzzy numbers. This answered the third and fourth research questions. The analyses allowed for the development of a fuzzy model for determining the time buffer size. To achieve conclusions of fuzzy sets, the model applied a method of the "middle best sector" (MBS). The model was applied in the MATLAB software to estimate the buffer size using the Project Manager.

The model was applied in practice in a technical production preparation project for a new product in one Polish enterprise. The research results indicate that the developed fuzzy model for determining the time buffer size is efficient as it shortens the total project duration while preserving aggressive task times and guaranteeing a 90 % probability of project timely execution. As a result, unwanted situations can be eliminated from the project, such as the student syndrome, Parkinson's law, overestimating of task duration, and multitasking. Moreover, the developed model was compared with other methods, such as half of the time total of a path, the sum of squares (SSQ), and the root square error method (RSEM). The analysis results indicate that the developed model may not shorten the total project duration time by 25 %, such as the method of half of the times total of a path, or by 35 %, such as the SSQ method, but merely by 5 %. However, it guarantees a 90 % probability of timely project execution. Thus, a positive answer was received to the last research question regarding the guaranteed 90 % probability for timely project execution. Hence, the research problem has been solved.

As the research results are satisfactory and characterised by possible practical application in projects, it is expected that further future research will be performed to search for the possibility of the development and application of a fuzzy model in determining time buffer size in a critical chain programme.

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Model for assessing engineering competencies of logistics specialists in transport organisations

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ABSTRACT
In today's dynamic, technology-driven, and diverse world of knowledge society, transport organisations should purposefully analyse and assess their operations since they often have to face problems emerging from the lack of knowledge and competencies of logistics specialists. The engineering competencies of logistics specialists are highly appreciated in transport systems. However, the selection of assessment criteria and determination of its importance is a difficult task for managers in this sector. Thus, it is reasonable to apply the multi-criteria methodologies, such as SAW, AHP, MOORA, and VIKOR, whilst determining the importance of criteria describing the competencies of logistics specialists in a transport organisation. Applying the multi-criteria methods provides prerequisites for an objective, precise, and the least time-consuming way to evaluate the engineering competencies of logistics specialists. The analysis of the results enables the most suitable decisions to utilise the significant potential of logistics specialists. The article examines the problem areas for evaluating the competencies of logistics specialists. The current paper presents the evaluation of logistics specialists' competencies based on the methodology used to determine the importance of criteria (SAW and AHP methods). Additionally, further recommendations are suggested to effectively manage certain corrections on competencies in transport organisations under investigation.

KEY WORDS
logistics, transport, logistics specialists, competencies, engineering competencies, assessment methods, SAW, AHP

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Introduction

The primary and most important resource in modern transport organisations is the competencies of logistics specialists (Gupta et al., 2022; Koh & Yuen, 2022; Kohl et al., 2020). Effective utilisation of these competencies requires analysis of their content, managing the knowledge process, and constantly renewing it. The majority of researchers emphasise the importance of competencies in ongoing operations. For instance, Doyle et al. (2017) investigated the demand for personnel competencies in biology,

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Mulyanto et al. (2018) based their research on the environment, Golden and Hanlon (2018), Hartmann et al. (2021), Violato (2018), Kurnia et al. (2019) focused on medicine, Rullani et al. (2016) — economics, Najat (2017), Ketonen-Oksi (2022) — management, Andersson et al. (2016), Yaghi, Sindi (2016), Trusculescu et al. (2016), Wringe (2015), Wood et al. (2018) — philosophy, Galustyan et al. (2020) — areas of information technologies. Most of these researchers highlighted the benefits of knowledge as a form of competency, supported the idea of improving competence assessment (Wu et al., 2021), and discussed the questions of competence management (Lindgren et al., 2015).

Competencies are undisputedly important (Patalas-Maliszewska & Kłos, 2019); however, a disagreement exists regarding the competencies necessary for a logistics specialist to perform effectively in a workplace. Some authors consider creativity (Jankelova, 2022; Tsonkova, 2020), and others (Chand et al., 2022; Chowdhury & Murzi, 2020; Machado & Freiling, 2023; Suksanchananun et al., 2020) believe teamwork and engineering competencies are the most important. Several researchers (Martínez-Sánchez et al., 2020) claim that education is one of the principal factors for a successful career. The present paper lists the essential engineering competencies and their assessment criteria selected from a plethora of characteristics of engineering competence.

Diverse methods and models have previously been proposed and developed to solve different logistics tasks. Certain methods and models are specifically based on mathematical calculations, whilst others depend on qualitative dimensions. The selection of methods largely depends on the goal. However, competencies assessed following the same selected criteria are assigned to a group of multi-criteria tasks. Many researchers (Dweiri et al., 2017) state that assessment methods should be simple and easy to understand, and provide opportunities to obtain sufficiently accurate results. Thus, the selected assessment method should be characterised by constant results and be easily applicable to a transport organisation. The SAW method (Drejeriene & Drejeris, 2017; Skačkauskienė & Katinienė, 2017) fully meets these requirements. Estimates obtained by this method accurately reflect the competencies of logistics specialists evaluated following the selected criteria. It is also reasonable to apply the AHP method to research the competencies of logistics specialists, as it has an advantage over other multi-criteria decision-making methods. The AHP method is more flexible and convenient for decision-makers to verify the consistency of expert judgements.

Among the multi-criteria methods analysed by the authors of this paper, MOORA and VIKOR are also exceptional as they can be suitable for developing a tool to evaluate the competencies of logistics specialists in a transport organisation. These methods enable the identification and comprehensive evaluation of the competencies of logistics specialists in a transport organisation. If possible, SAW, AHP, MOORA, and VIKOR methodologies should be used simultaneously to assess the competencies of logistics specialists and eliminate the chances of subjectivity. The results of such an assessment are beneficial for improving management processes of labour resources. Additionally, it would provide valuable information on the competencies of logistics specialists in transport organisations and enable chief executives to come up with impartial solutions associated with employee salary ranges. These methods would also abate employee selection to corresponding positions and finding and applying the best and the most transparent incentives.

The research aimed to develop a methodology for assessing the competencies of logistics specialists in a transport organisation, which would be used to objectively/scientifically evaluate these competencies under real business conditions. It is, thus, obvious that the demand for engineering competencies of logistics specialists varies in different companies. Therefore, developing a universal assessment tool suitable for any logistics company is highly anticipated. In this case, it is confirmed that the assessment of competencies should be treated as a multi-criteria task, which would be solved using the multi-criteria assessment methods. The following research methods were used: comparative analysis, synthesis, expert assessment, and multi-criteria evaluation methods SAW and AHP.

1. Literature review

1.1. Content of the competencies of logistics specialists in transport organisations

Transport organisations are obliged to monitor changes, evaluate the competencies and qualifications of logistics specialists, improve work conditions and create an environment where they would willingly share their expertise, thus bringing new knowledge and substantial advantages to the company. Wang and Hsieh (2013) claimed that social and professional competency affects a company's growth and contributes to achieving professional goals by encouraging employees to apply their highest potential and abilities. According to Martinez-Sanchez et al. (2020), it is necessary to evaluate the levels of education and competencies of logistics specialists in assessing the effects of technological development on employee retention in transport organisations.

The competencies of logistics specialists in a transport organisation can be defined by individual characteristics, work culture, qualifications and creativity required to implement organisational goals (Jankelova, 2022; Taguma & Anger, 2015; Tsonkova, 2020).

The importance of engineering and social competencies for the future is highlighted by Hau et al. (2013). The authors claimed that in the fourth industrial revolution, robots would fully replace human input by using information technologies and algorithms. However, certain social competencies, such as motivation and creativity, cannot be replaced by robots.

Thus, many authors (Hau et al., 2013) perceive motivation as a driving force and a powerful tool to complete important tasks and jobs. The advantages of social and engineering competencies and teamwork were stressed by Chowdhury and Murzi (2020) and Chand et al. (2022), who argued that the decline in physical, manual skills and basic cognitive knowledge would greatly increase the demand for social and technological competencies in the industry. According to Taguma et al. (2018), logistics specialists must constantly acquire new technological and engineering skills to remain competitive in the labour market. These skills, in turn, require such characteristics as curiosity, flexibility, independence and a positive attitude towards lifelong learning.

Incompetence in technologies disrupts overall operations in transport organisations. According to Aloqaili et al. (2020), selecting an appropriate technological development for transport organisations becomes less complicated than their actual introduction or convincing employees to use it.

These processes must be managed by logistics specialists using their technological knowledge to attain an effective and rapid execution of transportation processes (Aloqaili et al., 2020). The engineering competence of logistics specialists comprises the most advanced knowledge, technical and coding skills, general understanding of logistics, and IT security processes (Kaur et al., 2020; Mikl, 2021).

Engineers may review/evaluate/prepare plans, specifications, calculations, and/or other engineering documentation, provide recommendations for higher-level engineering operations, analyse and design works of limited scope and complexity/execute inspections/audits/investigations, and provide consultations.

An engineer must effectively communicate with private and legal entities to explain standards and regulations or provide technical assistance (Litvinenko et al., 2022). They may be responsible for analysis or design to determine project implementation or continuity options, project review/approval; execution and supervision of infrastructure projects, and reassuring project implementation. A technical expert is a distinguished position of high engineering complexity, which may include supervisory duties. Engineers plan and manage large and complex projects/programmes independently and take responsibility. Additionally, they evaluate the completion of tasks and common achievements with technical accuracy, adhere to goals, and wait for the manager's approval to execute complex operations. Also, engineers must ensure quality standards, supervise operations and plan budgets (Młody et al., 2023; Peña et al., 2023). Communication with other specialists and

Tab. 1. Key competencies of logistics specialists

Group of explicit competencies	Code	Group of tacit competencies	Code
Use of information technologies (technically complex) in transportation process	I_1	Work complexity	N_1
Evaluation of the specifications of vehicle control systems	I_2	Employee influence on the realisation of organisational goals	N_2
Knowledge of vehicle technical assistance standards	I_3	Work culture	N_3
Preparation of engineering documentation	I_4	Creativity	N_4
Maintaining technological infrastructure in a transport organisation	I_5	Motivation to work	N_5
Consultations provided	I_6	Autonomy at work	N_6

professionals is also required. Engineers represent their organisations as experts. Singh and Fleming (2010) and Karácsony and Bokor (2021) argue that cooperation between logistics specialists improves the quality of competencies and economic value for transport organisations.

The essential and necessary competencies are selected from various engineering characteristics and grouped into two categories, i.e., explicit and tacit competencies (Table 1).

The following characteristics are linked to the direct function of the work executed by logistics specialists and are attributed to engineering competence: use of information technologies (technically complex) in the transportation process, knowledge of vehicle technical assistance standards and management of such systems, preparation of engineering documentation, and maintaining technological infrastructure.

Other competencies required for a logistics specialist are work complexity, employee influence on the realisation of organisational goals, work culture, creativity, motivation to work, and autonomy.

These competencies are not directly linked to work performed by a logistics specialist and may be applicable to all specialists (Hernandez-de-Menendez et al., 2020); however, they are inseparable from the competencies of a logistics specialist.

1.2. Criteria for evaluating competencies of logistics specialists in transport organisations

Regardless of the evidence confirming transport company's success linked to employee competencies, research has been scarce and methodological potential to measure competencies is insufficient and needs to be adjusted (Kilibarda et al., 2020; Sapper et al., 2021). Competence assessment methods are usually based on one criterion. The emphasis is usually placed on selecting such a criterion or measuring a certain element in a business sector. However, no attention is given to evaluating the engineering competencies of logistics specialists or offering objective, qualitative assessment methodology.

It is necessary to analyse the content of the existing competencies and its assessment criteria in the overall evaluation of logistics specialists employed in transport companies. The content analysis of the competencies provides more information on the specific and mastered competencies and their effects on the company's activities. The variety of criteria reflects the importance of specific competencies while more detailed results on assessing the researched competencies are obtained.

There are twelve distinguished assessment criteria based on the contents of engineering competencies. Therefore, the importance of competencies can be thoroughly researched (Fig. 1).

The research findings by Salazar et al. (2019) show that teams at transport companies are more likely to sustain in a competitive environment if they have interdisciplinary knowledge. This knowledge and skills are especially valuable in pursuing leadership (Salazar et al., 2019). The wider the spectrum of this knowledge and the ability to apply it interdisciplinarily, the better (Van Den Beemt et al., 2019). Such engineering knowledge is not required in all transport companies; however, having at least a minimal interdisciplinary knowledge shows a greater

Fig. 1. Criteria for evaluating competencies of logistics specialists in a transport organisation

competence of logistics specialists. Interdisciplinary knowledge is a more important evaluation criterion in small engineering companies where employees are assigned more than one function and are generally more responsible for performance results. Sabirov et al. (2021) argued that a greater number of completed educational (higher and vocational training) institutions leads to different possibilities for qualification development. Continuous qualification improvement is necessary to express engineering competence (Sabirov et al., 2021). Qualification is formalised, systemised and documented knowledge associated with a professional career covering a particular professional area. Thus, specialists of various professions must have professional knowledge (Manuel, 2017), subject skills, and abilities to perform tasks according to the relevant work field (Metro et al., 2019). The qualification granted by an educational institution may prove the value of an employee (Liu et al., 2020; Shmatko et al., 2020). The criterion of qualification improvement has a major impact on the existing competencies of a transport specialist and the overall assessment of their competencies; thus, it should be included in the criteria evaluation system (Dundiuk, 2021). Walker (2014) noted that general learning and improvement of qualifications in transport companies is achieved by correcting errors made by specialists. Error correction provides valuable insights and promotes new measures to be implemented to avoid failures in the future. Certain changes in the company's activities create conditions for the emergence of contradictions in the already established service provision rules. These contradictions appear due to human errors, which, in turn, are hard to avoid under numerous rules or when the need arises to alter them. Urbaitė (2020) emphasised one specific criterion, i.e., the ability to analyse and correct mistakes. According to Krishnan et al. (2017), Voline et al. (2019), Schwartz et al. (2017) and Brown (2019), one of the most important criteria associated with solving problems emerging from human errors is quick decision-making. This criterion requires the mastery of specific competencies. In particular, the demand for specific competencies may be a decisive criterion; thus, constant professional improvement possibilities are necessary to evaluate engineering competencies in the context of the modern industrial revolution. This criterion also determines the aspiration of employees to meet the challenges of global society and the requirements of contemporary businesses (Flores et al., 2020). The modern business approach strives to connect engineering solutions with operational sustainability; thus, the concepts of sustainable business model (Bocken et al., 2014) and sustainable technology (Heiskanen et al., 2005) emerge in tech businesses.

The use of these categories becomes inseparable from many technical solutions in engineering operations. Drejeris & Oželiene (2019) argued that sustainable development was undoubtedly more profitable than non-sustainable; thus, it is necessary to draw attention to attitudes, ideas and possibilities of the transport company's personnel to develop sustainable technologies in assessing engineering competencies. The number of ideas provided by logistics specialists in a transport company definitely indicates creativity. According to Bloom et al. (2019), creativity and innovativeness can be expressed as the number of ideas presented over a certain period. The ideas must be clarified and presented under real conditions while assessing the logistics specialists' competencies. Creativity and innovativeness are necessary characteristics for logistics specialists and technical personnel. Thus, the assessment of engineering competencies should include the criterion of the number of innovative ideas implemented over a certain period, for instance, five years. Pedron (2018) stated that tasks requiring creativity and emotional intelligence have been transferred to technological literacy. The assessment based on technological literacy encompasses the most advanced knowledge, technical and coding skills, process understanding and IT security awareness (Kaur et al., 2020). In their analyses of competencies, Bloodgood (2019) and Zhao et al. (2020) argued that IT knowledge transfer and co-worker education should provide specialists with the ability to apply innovations and improve technologies used in diverse knowledge processes. Therefore, the knowledge acquired and transferred to other employees or cooperation is an important factor in competence assessment. A logistics specialist needs language skills to convey information and train other transport company employees. Language skills are an integral part of the qualification, enabling access to the latest information, cooperation and exchanging experiences with colleagues worldwide (Karácsony & Bokor, 2021; Tiškus, 2019). Rahman et al. (2019) and Albantani and Madkur (2018) claimed that it was necessary to integrate foreign languages into the higher education system to raise the competencies of prospective employees. Proficiency in foreign languages would help update logistics specialists' knowledge and skills. Tsekeris (2019) argued that logistics specialists were required to update their technical and digital skills. In their research on operational skills and competencies, Fahmi and Ali (2022) claimed that work experience greatly impacted the quality of operational performance, project success, effective management of work equipment and technologies, decision-making, career planning and achieving transport company's goals. Thus, employees with more work experience will be more confident in their decisions, have more authority and, possibly, greater influence on others and carry out more specific tasks.

2. Research methods

Certain aspects must be considered upon completion of the content analysis on multi-criteria methods. First, the possibilities of deploying these methods in establishing competence criteria and evaluation systems for logistics specialists must be explored. Second, this method's results should be applied constantly, have low costs in terms of time, and the method should be easily implemented in the company (Skačkauskienė & Katinienė, 2017). The most suitable methods for evaluating logistics specialists' competencies are as follows: (1) SAW, which is based on the concept of finding the weighted sum of the performance of each alternative on all attributes (Aisyah, 2021), (2) AHP — the hierarchical structuring of the components considering their importance (Vaičiūtė et al., 2022); it uses pairwise comparison of the alternatives, (3) MOORA — a multi-objective optimisation based on ratio analysis consisting of two parts: the ratio system and the reference point approach (Fajar & Sarno, 2019), and (4) VIKOR, which determines the compromise ranking list aimed at optimising complex multi-criteria systems (Opricovic & Tzeng, 2004). The MOORA and VIKOR methods were refused as they were designed to optimise complex and multi-objective systems. The SAW and AHP methodologies were selected to research and evaluate the logistics specialists' competencies based on criteria.

The multi-criteria assessment methods were applied to evaluate the engineering competencies of logistics specialists in a transport organisation. An algorithm consisting of four stages was developed. The first stage is preparation, i.e., familiarisation with the transport company's management and organisational structure and discussion of the importance of researching competencies and expected results. This stage requires to form a group of experts selected according to certain criteria. The data on the criteria significance is required in SAW and AHP applications. The second stage is consulting, i.e., interviewing expert groups and logistics specialists. This stage requires providing the main concepts and discussing the peculiarities of the research. The third stage is interviews with experts and logistics specialists. The compatibility of data matrices and expert opinions is calculated. In the event of non-consistent opinions between data matrices and expert opinions, a regress to stage two is made. If the opinions are consistent, the results are summarised. The fourth stage processes data, and the transport organisation is introduced with evaluation results to be used by the management for effective solutions to improve logistics specialists' performance results, such as adjusting or completely changing objectives, setting new qualification improvement tasks, changing careers, using the company's strengths and eliminating its weaknesses. These changes could produce a safer environment in transport organisations, prompt logistics specialists to complete the assigned tasks faster and strengthen cooperation.

The SAW method was suggested for evaluating the competencies of logistics specialists in a transport organisation. The AHP method is applied in the case of a doubt about the reliability of the results.

The evaluation criteria for assessment must be as objective as possible (Drejeris & Miceikiene, 2018). A scale of 100 points was selected to evaluate the criteria, and the overall estimates were calculated as follows:

$$W_i = \sum_{e=1}^{n} W_{ie}\,,\ i = (1, \dots, m) \qquad (1)$$

here, W_i — the sum of all evaluations provided by the experts, W_{ie} — evaluation of the i-th criterion by the e-th expert, n — the number of experts, and m — the number of criteria.

The equation below is used to determine the relative importance of one of the questions:

$$n_i = \frac{W_i}{\sum_{i=1}^{m} W_i},\ i = (1, \dots, m) \qquad (2)$$

here, n_i — the importance and $\sum_{i=m}^{m} W_i$ — the sum of all i criterion estimates by all experts.

Thus, the sum of the importance of all criteria will be equal to 1:

$$\sum_{i=1}^{m} n_i = 1 \qquad (3)$$

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The compatibility between expert opinions and the expert evaluation is assessed using the SAW and AHP methods.

The calculated competence coefficient, i.e., compatibility of opinions, determines and evaluates the competence of each expert.

Baležentis and Streimikiene (2017) suggested providing the same competence coefficient for all experts in the formula. Giving equal weight to all experts indicates that expert opinions are consistent and competent.

$$K_j^0 = \frac{j}{n}, j = 1, \ldots, n \quad (4)$$

here, K_j^0 — expert competence coefficient, j — the coefficient equal to 1, and n — the number of experts.

$$X_j^t = \sum_{i=1}^{m} K_i^{t-1} \cdot x_{ij}, \; j = 1, \ldots, n \quad (5)$$

here, X_j^t — new matrix values, $\sum_{i=1}^{m} K_i^{t-1}$ — group assessments, x_{ij} — i-experts, and j — the alternative rank.

$$\lambda^t = \sum_{j=1}^{n} \sum_{i=1}^{m} x_j^t \cdot x_{ij} \quad (6)$$

here, λ^t lambda — all matrices, x_j^t — the sum of values, n — the number of experts, and m — the number of alternatives.

$$K_i^t = \frac{1}{\lambda^t} \cdot \sum_{j=1}^{n} x_j^t \cdot x_{ij}, \; \sum_{i=1}^{m} \; K_i^t = 1 \quad (7)$$

The sum of all evaluation weights provided by each expert c_{ik} should be equal to 1 (or 100 %) when applying the direct method of criteria-weighting. The method here indirectly determines criteria weights and deploys a selected scoring system (5, 10, 20 and others). Evaluations may be repeated.

$$w = \frac{\sum_{k=1}^{r} c_{ik}}{\sum_{i=1}^{m} \sum_{k=1}^{r} c_{ik}} \quad (8)$$

Expert assessments are marked c_{ik} (i = 1,..., m; k = 1,..., r), where m — the number of the applied criteria and r — the number of experts. Expert rank assessments are presented in the matrix of indicators (Table 2).

The expert group n evaluates objects m quantitatively. The evaluations form a matrix of n rows and m columns (Šakalys et al., 2019). The evaluation can act as an indicator unit, part of a unit, a percentage or as a ten-point grading system. The ranking of expert indicators is suitable for calculating the concordance coefficient. The ranking is a procedure that gives the most important indicator a rank (R) equal to one, the second indicator — the second rank, and the last indicator — rank m (where m is the number of comparative indicators).

If the value of the calculated concordance coefficient W is close to 1, then it is possible to conclude that expert evaluation is consistent. The compatibility of expert evaluation is considered sufficient if the value of the concordance coefficient W reaches 0.6 or more.

Normalisation formula used in the SAW method to evaluate competencies:

$$\bar{r}_{ij} = \frac{r_{ij}}{\sum_{j=1}^{n} r_{ij}} \quad (9)$$

($\sum_{j=1}^{n} r_{ij}, \; \bar{r}_{ij} = 1$), here, r_{ij} — the value of the i-th criterion for the j-th alternative.

The criterion Sj in the SAW method is calculated according to the formula:

$$S_j = \sum_{i=1}^{m} w_i \, \bar{r}_{ij} \quad (10)$$

here, w_i is the weight of the i-th criterion.

Experts determine the maximum (minimum) value of each criterion. The value of the maximising criterion $\bar{r}_{ij}$ is calculated according to the formula:

$$\bar{r}_{ij} = \frac{r_{ij}}{max \, r_{ij}} \quad (11)$$

Tab. 2. Matrix of evaluation indicators

Expert code		**Indicator marker,** j = 1, 2, ..., m				
X_1		X_2	X_3	...	X_m	
i = 1, 2, ..., n	E_1	R_{11}	R_{12}	R_{13}	...	R_{1m}
	E_2	R_{21}	R_{22}	R_{23}	...	R_{2m}
	E_3	R_{31}	R_{32}	R_{33}	...	R_{3m}
	...	...	...	...	...	...
	E_n	R_{n1}	R_{n2}	R_{n3}	...	R_{nm}

Source: Elaborated by the author based on Sivilevičus, 2019.

The value of the minimising criterion $\bar{r}_{ij}$ is calculated according to the formula:

$$\bar{r}_{ij} = \frac{min\, r_{ij}}{r_{ij}} \quad (12)$$

here, $max\,\bar{r}_{ij}$ $(min\,\bar{r}_{ij})$ is the maximum (minimum) value of the i-th criterion determined by the experts.

The maximum theoretical value of the S_j criterion is equal to one. The most convenient way to demonstrate the S_j value is on the scale of percentages. The object comparison with the maximum value (100 %) is reflected on this scale (Podvezko, 2011).

The authors of this article suggest conducting an evaluation of the competencies of logistics specialists based on the methodology presented in Table 3.

The steps of forming a group of experts, analysis of a set of criteria, and research preparation are carried out during the preparation stage. These steps must be taken consistently, and the sequence should not be altered.

The step of forming a group of experts begins with determining the expert selection criteria (education, the number of completed projects, and work experience). Also, this step involves an interview with management staff to address the time required for research execution, expert competencies, and the number of experts partaking in the research. The selection criteria may vary, depending on the areas of the organisation's expertise. Usually, experts are selected on the basis of their professional competencies, i.e., work experience, seniority, scientific degree,

Tab. 3. Methodology for evaluating competencies of logistics specialists in transport organisation

Stage in evaluation methodology	Steps	Sequence of methodology applications in assessing the competencies of logistics specialists
Preparation for the evaluation	1.1. Forming a group of experts	1.1.1. Conducting an interview with management staff in the transport organisation regarding the selection of experts. 1.1.2. Forming a group of experts and suggesting the following criteria for expert selection: (1) position held (manager, deputy manager, department or branch manager), (2) the number of participations in assessment groups (for instance, audit or project groups), and (3) work experience (at least three years in the field of research) 1.1.3. Confirming the structure of the group.
	1.2. Validation/analysis/ compilation of a set of criteria	1.2.1. Reviewing a collection of explicit and tacit competencies (if there is a need to change the criteria, managers/the group of experts are the ones to suggest it during interviews) 1.2.2. Selecting an assessment scale
	1.3. Research preparation	1.3.1. Selecting the type of questionnaire 1.3.2. Preparing the research instrument 1.3.3. Preparing instructions for filling in the questionnaires
Consultation	2.1. Organising interviews	2.1.1. Conducting an interview with the management of the transport organisation 2.1.2. Conducting an interview with logistics specialists 2.1.3. Conducting an interview with the group of experts
Evaluation	3.1. Evaluating the competencies of logistics specialists and determining the significance of criteria	3.1.1. Surveying a group of experts: 3.1.1.1. Assessing the criteria 3.1.1.2. Evaluating the competencies of logistics specialists according to the criteria while using the ranking method 3.1.1.3. Evaluating the competencies of logistics specialists by pairwise comparison method 3.1.2. Surveying logistics specialists
	3.2. Determining the degree of compatibility of expert opinions	3.2.1. Calculating the degree of compatibility of expert opinions 3.2.2. Calculating the competence coefficient of experts
	3.3. Calculating the significance estimates of the competence criteria	3.3.1. Calculating the significance estimates of explicit and tacit competencies' block 3.3.2. Calculating the significance estimates of the criteria
Summary of the results	4.1. Data processing	4.1.1. Normalising explicit competencies of logistics specialists 4.1.2. Normalising tacit competencies of logistics specialists
	4.2. Synthesis of the competence values of logistics specialists	4.2.1. Calculating the estimates of explicit competencies' block of logistics specialists 4.1.2. Calculating the estimates of tacit competencies' block of logistics specialists Integrating estimates of all competencies into a generalised estimate 4.2.3. Integrating estimates of all competencies into a generalised estimate

research activities, and abilities to solve specific problems in the relevant field. An expert group is formed following the criteria specified in Point 1 of the methodology, or these criteria are determined by the management staff of the transport organisation. The number of experts in the group for evaluating the logistics specialists' competencies is determined by the management staff and the evaluator during the interview. The recommended number is no less than three to guarantee a better distribution of opinions and no more than ten for results to be objective and reliable (Podvezko, 2011). The optimal number of expert groups varies between eight to ten members, and at least five experts should be surveyed. The reliability of evaluation slightly increases as the number of experts maximises; however, the greatest accuracy of the estimates can be obtained with 5–9 experts in a group.

Next, the collected competencies of logistics specialists are analysed. The management staff and experts analyse the content of elicit and tacit competencies and may alter/eliminate the irrelevant ones. The evaluator, the management staff and/or the expert group review the criteria evaluation.

The research sample is calculated during research preparation. This step also involves selecting the questionnaire type and preparing the filling instructions. Then, interviews are organised, and instructions are provided for logistics specialists and experts during the stage consultations. The evaluation stage has three steps: evaluating the competencies of logistics specialists, determining the degree of compatibility of expert opinions and calculating the criteria significances. These steps involve formalised surveys of logistics specialists and experts. Questionnaires distributed to logistics specialists supply data on the existing competencies in general and those applied in everyday operations. Experts receive different questionnaires developed by an evaluator. These questionnaires are specially designed to be used with the SAW and AHP methodologies. Experts evaluate the groups of elicit and tacit competencies (AHP method) and those based on certain criteria (SAW method).

The summary of the results involves the following steps: data processing and synthesis of the competence values of logistics specialists. The evaluator summarises the obtained data and values for competence groups. Then, the results are visualised and presented to the management staff and logistics specialists of the transport organisation.

3. Research results and discussion

Empirical research based on the SAW method was conducted to verify the suitability of the developed methodology for evaluating the competencies of logistics specialists. The AHP pairwise comparison method was used to determine the significances. To be eligible for research, transport companies had to meet the following criteria: no less than five years of operation and the number of employees attributing the transport company to one of the four business types: large, medium, small, and very small. Financial data was also taken into consideration, i.e., the annual income of the company had to be no less than EUR 2 million. Generally, large transport organisations were split into subdivisions, which were evaluated. The number of logistics specialists in subdivisions usually did not exceed the average number of members in a transport organisation.

Two transport organisations were selected for this research based on the criteria mentioned above. They have two subdivisions in Lithuania and two more in Latvia (Table 4).

Forming a group of experts. There were three main criteria in the expert selection process: no less than five years of managerial experience, participation in no less than two projects or working groups and no less than ten years of experience in the transportation business. This way, nine experts from different transport organisations were chosen: two from Latvia, two from the Netherlands, and five from Lithuania. The average managerial experience of the experts was 10.4 years, and the average work experience was 16.5 years. On average, each expert took part in three projects or working groups.

The collection of major criteria that directly impact the competencies of logistics specialists is based on the research by Skačkauskienė et al. (2017). The criteria were selected and categorised into two groups of competencies according to their type (explicit and tacit) and form of evaluation, i.e., qualitative or quantitative (Points 1.2.1, 1.2.2 and 1.2.3 in Table 3).

Research preparation. Different questionnaires were designed for experts and logistics specialists to evaluate competencies and criteria using two methods, i.e., SAW and AHP. Instructions specifying the task for experts, main concepts and filling directions were prepared.

Tab. 4. Characteristics of the researched transport organisations

Title	No. of logistics specialists	Justification of the competencies of logistics specialists		Brief description of activities
JSC X transport	89	58 — professional bachelor's degree, 27 — bachelor's degree, 4 — master's degree	For interested/motivated employees: mechanics courses, internships at vehicle manufacturers.	Transport organisations. Transportation of passengers and cargo by diverse modes of transport. Subdivisions were categorised based on countries and activity directions.
JSC X I — subdivision	11	5 — master's degree, 3 — bachelor's degree	For interested/motivated employees: mechanics courses, internships at vehicle manufacturers.	
SIA B Transport	78	30 — professional bachelor's degree, 32 — bachelor's degree, 16 — master's degree	For interested/motivated employees: mechanics courses, internships at vehicle manufacturers. Courses on IT system development (obligatory for master's graduates).	
SIA B I — subdivision	7	2 — professional bachelor's degree, 3 — bachelor's degree, 2— master's degree	For interested/motivated employees: mechanics courses, internships at vehicle manufacturers. Courses on IT system development (obligatory for master's graduates).	

Tab. 5. Criteria estimates of the competencies' blocks by the SAW method

Criteria	Experts									In total	Significances
	E1	E2	E3	E4	E5	E6	E7	E8	E9		
KR1	8	10	8	10	9	8	9	10	9	81	0.090
KR2	8	7	9	9	10	10	9	8	7	77	0.086
KR3	10	10	9	10	10	10	10	10	10	89	0.099
KR4	9	7	6	5	5	7	7	8	5	59	0.066
KR5	10	10	9	10	10	9	10	9	10	87	0.097
KR6	8	7	7	6	7	6	6	6	6	59	0.066
KR7	7	8	7	7	9	8	9	8	10	73	0.081
KR8	8	9	9	10	9	9	8	8	9	79	0.088
KR9	8	9	10	9	8	10	9	10	10	83	0.092
KR10	6	8	7	7	5	5	6	6	7	57	0.063
KR11	8	7	10	8	8	8	7	9	8	73	0.081
KR12	10	8	9	9	10	10	10	8	9	83	0.092
Total	100	100	100	100	100	100	100	100	100	900	1

Organising interviews. The interviews with logistics specialists and a group of experts were conducted separately, considering the differences in questionnaires. During the consultation, the content of competencies and criteria was explained, instructions on filling out the questionnaires were given, and questions were answered.

Evaluating the competencies of logistics specialists. The survey method was used together with SAW. Experts were asked to evaluate the significances of each group and the criteria of competencies specified in each questionnaire.

The evaluation criteria for engineering competencies of logistics specialists were based on a scientific literature analysis and synthesised opinions and interpretations from various researchers. The following measurement units were assigned to the criteria of engineering competencies of logistics specialists:

KR1. Interdisciplinary knowledge (the number of operational duties — units, points).

KR2. Education (the number of qualifications granted by educational institutions — units, points).

KR3. Professional knowledge (the number of mastered systems used at transport organisations — units, points).

KR4. Qualification improvement (the number of hours of the completed courses — units, points).

KR5. Error analysis and correction (the number of errors (associated with technological development) prior to and after qualification improvement — units, points).

KR6. Decision-making (the position held — units, points).

KR7. Employee attitudes, ideas, and possibilities for developing sustainable technologies (knowledge and opinions towards sustainable technologies, abilities to apply sustainable methods that reduce pollution and waste — units, points).

KR8. A number of innovative ideas realised over a certain period (the number of years worked in a company — units, points).

KR9. Technological literacy (the number of completed courses on technologies — units, points).

KR10. Knowledge acquisition and transfer (the number of cases of transferred knowledge, i.e., consultations provided to other co-workers and employees — units, points).

KR11. Knowledge of foreign languages (the number of languages learned and the level of proficiency — units, points).

KR12. Work experience (the number of years — points).

It is worth noting that the values of all distinguished criteria become better when they are higher, i.e., these criteria are maximised; thus, the calculation of the estimates of engineering competencies becomes substantially simpler and faster.

It is also important to draw attention to the fact that final significances by the experts have the following distribution: 0.41 for the group of tacit competencies and 0.59 for the group of explicit competencies. According to experts, the most important criteria are professional knowledge (KR3) with 0.099 and error analysis and correction (KR5) with 0.097. The equal values were given to the criteria of technological literacy (KR9) and work experience (KR12). The criterion of interdisciplinary knowledge (KR1) with 0.090 was also in the top five (Table 5).

The evaluation of logistics specialists' engineering competencies using the SAW method entails determining the value of each competence according to the criterion specified in the questionnaire. The greatest significances and equal distribution can be detected in the group of tacit competencies: 0.22 (N_5 — motivation to work), 0.21 (N_2 — employee's influence on the realisation of organisational goals), 0.2 (N_6 — autonomy at work) (Table 6). This distribution indicates that experts have similar attitudes concerning the importance and impact of these competencies on logistics employee results.

The greatest significances are given to the knowledge of vehicle technical assistance standards (0.28) in the group of explicit competencies, while motivation to work excelled in the tacit group (0.22) (Table 6).

Experts ranked the competencies of logistics specialists according to their importance (from 1 as the most important to 6 as the least important). The distribution of the sum of ranks is presented in Table 7.

The following estimates in the group of explicit competencies were ranked the same: knowledge of vehicle technical assistance standards and the evaluation of the specifications of vehicle control systems are ranked as first, fifth and sixth, respectively. The ranking and evaluation process of tacit competencies motivation to work, autonomy at work, and work complexity received unanimous significances and positions were equally distributed, i.e., first, third and sixth (Fig. 2).

Experts evaluated the competencies of logistics specialists based on 12 criteria (where 10 was the most important and 1 was the least important). These values could repeat. The sum of values and distribution of final values is presented in Table 8.

To summarise, the sequence of criteria changed with expert evaluation. Only one congruence of the rank (N6) was detected in the group of tacit competencies.

Expert survey (AHP method). Expert questionnaires were designed and adapted to the AHP method. Each expert was given separate tables representing competence groups (e.g., Table 9), instructions for filling out the questionnaire, main concepts and evaluation scales. The attached AHP instruction specifies tasks for experts, i.e., to perform a pairwise comparison of the competencies. The examples of comparing statements were also attached to the instruction. In the case of uncertainties, experts were consulted via mobile and online chat platforms.

Experts evaluated the competencies of logistics specialists based on the selected scale from 0 to 9 (Table 10). Each numerical value corresponds to qualitative (verbal, linguistic) evaluation. It is convenient to choose a scale with more numerical values in the case of a large number of the evaluated competencies. It should be emphasised that diverse versions of the evaluation scale are possible:

0 ÷ 1 — possible values {0; 0,5; 1};

0 ÷ 9 — possible values {0; 1; 2; 3; 4; 5; 6; 7; 8; 9}.

Tab. 6. Competency estimates by the SAW method

Experts / Competencies	E1	E2	E3	E4	E5	E6	E7	E8	E9	Final significances	Ranks
Group of explicit competencies											
I_1	0.15	0.3	0.2	0.13	0.2	0.47	0.1	0.1	0.35	0.22	2
I_2	0.13	0	0.2	0.3	0.3	0.13	0.3	0.2	0.2	0.2	3
I_3	0.27	0.5	0.3	0.27	0.3	0.2	0.3	0.13	0.3	0.28	1
I_4	0.1	0	0.1	0.05	0.05	0.05	0.1	0.1	0.02	0.06	6
I_5	0.2	0.2	0.15	0.05	0.05	0.05	0.1	0.2	0.03	0.11	5
I_6	0.15	0	0.05	0.2	0.1	0.1	0.1	0.27	0.1	0.12	4
Group of tacit competencies											
N_1	0.2	0	0.2	0	0.1	0.1	0	0.1	0	0.06	6
N_2	0.15	0	0.2	0.5	0.2	0.15	0.5	0.15	0	0.21	2
N_3	0.1	0.3	0.1	0	0.2	0.23	0	0.1	0.1	0.13	5
N_4	0.23	0.2	0.2	0.3	0.2	0.22	0	0.22	0.2	0.19	4
N_5	0.22	0.5	0.2	0	0.1	0.23	0.05	0.23	0.4	0.22	1
N_6	0.1	0	0.1	0.2	0.2	0.07	0.45	0.2	0.3	0.20	3

here: the use of information technologies (technically complex) in transportation process — I_1, the evaluation of the specifications of vehicle control systems — I_2, knowledge of vehicle technical assistance standards — I_3, the preparation of engineering documentation — I_4, professional experience — I_5, maintaining technological infrastructure in transport organisation — I_6, work complexity — N_1, employee influence on the realisation of organisational goals — N_2, work culture — N_3, responsibility — N_4, motivation to work — N_5, autonomy at work — N_6, E1, E2 — experts from Latvia, E3, E4 — experts from the Netherlands, E5, E6, E7, E8, E9 — experts from Lithuania.

Tab. 7. Distribution of competence ranks by the SAW method

Group of explicit competencies						
	I_1	I_2	I_3	I_4	I_5	I_6
Sum of ranks	31	21	21	47	38.5	30.5
Final rank	4	1.5	1.5	6	5	3
Group of tacit competencies						
	N_1	N_2	N_3	N_4	N_5	N_6
Sum of ranks	45	42	44	33	26	37
Final rank	6	4	5	2	1	3

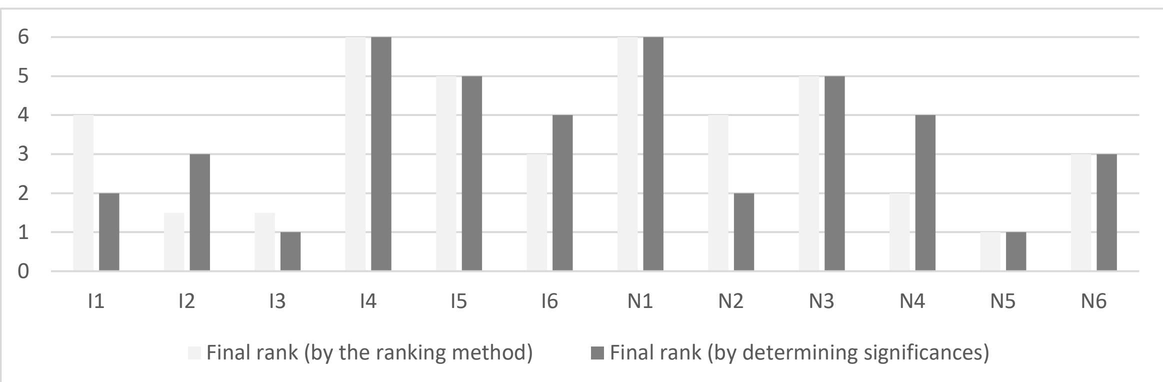

Fig. 2. Final ranks of competencies

Tab. 7. Distribution of competence ranks by the SAW method

GROUP OF EXPLICIT COMPETENCIES						
	I_1	I_2	I_3	I_4	I_5	I_6
Sum of ranks	31	21	21	47	38.5	30.5
Final rank	4	1.5	1.5	6	5	3
GROUP OF TACIT COMPETENCIES						
	N_1	N_2	N_3	N_4	N_5	N_6
Sum of ranks	45	42	44	33	26	37
Final rank	6	4	5	2	1	3

Tab. 8. Distribution of final ranks of logistics specialists' competencies based on the criteria

CRITERIA CODES AND THEIR COEFFICIENTS / COMPETENCIES	KR1	KR2	KR3	KR4	KR5	KR6	KR7	KR8	KR9	KR10	KR11	KR12	FINAL ESTIMATE	FINAL RANK
	0.09	0.085556	0.098889	0.065556	0.096667	0.065556	0.096667	0.081111	0.092222	0.063333	0.081111	0.092222		
I1	90	90	90	90	90	90	90	90	90	90	90	70	88.95556	2
I2	90	90	90	90	90	62	90	90	90	90	90	90	88.96444	1
I3	90	90	90	65	90	90	56	90	90	90	61	90	83.52222	4
I4	90	90	90	90	73	57	48	66	90	61	90	90	79.15	5
I5	90	58	90	90	90	90	90	90	90	90	90	90	88.06222	3
I6	90	62	90	61	90	58	90	62	51	90	50	90	75.29333	6
N1	90	90	90	90	90	90	90	90	90	90	90	90	90.8	1
N2	62	90	90	90	90	90	90	61	61	90	51	90	80.09	2
N3	45	90	45	45	45	50	90	50	45	90	90	48	61.11	6
N4	65	90	55	55	90	90	90	90	65	90	47	63	74.51111	4
N5	45	55	45	90	58	90	52	90	90	90	85	50	68.44444	5
N6	83	62	62	90	70	90	56	90	90	90	90	90	79.78556	3

Tab. 9. AHP table completed by an expert with pairwise comparison method

THE FIRST STATEMENTS OF THE GROUP OF EXPLICIT COMPETENCIES	THE SECOND STATEMENT OF THE GROUP OF EXPLICIT COMPETENCIES						
	Criteria	I_1	I_2	I_3	I_4	I_5	I_6
	I_1	1	7	5	1/3	8	3
	I_2	1/7	1	9	3	7	5
	I_3	1/5	1/9	1	8	7	5
	I_4	3	1/3	1/8	1	7	5
	I_5	1/8	1/7	1/7	1/7	1	5
	I_6	1/3	1/5	1/5	1/5	1/5	1

here: the use of information technologies (technically complex) in transportation process — I_1, the evaluation of the specifications of vehicle control systems — I_2, knowledge of vehicle technical assistance standards — I_3, preparation of engineering documentation — I_4, maintaining technological infrastructure in a transport organisation — I_5, consultations provided — I_6.

Tab. 10. Values of expert estimates

NUMERICAL VALUE	DESCRIPTION
1	The influence of both competencies on the work skills of a logistics specialist is the same.
3	The influence of one competence on the work skills of a logistics specialist is slightly greater compared to the other.
5	The influence of one competence on the work skills of a logistics specialist is average compared to the other.
7	The influence of one competence on the work skills of a logistics specialist is greater compared to the other.
9	The influence of one competence on the work skills of a logistics specialist is substantially greater compared to the other.
2,4,6,8	Intermediate values to be used in the case of doubt about the adequacy of odd estimates
1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9	Reverse evaluation

Source: Elaborated by the authors based on (Saaty, 1993).

Tab. 11. Expert competence coefficients

Expert competence coefficients								
E1	E2	E3	E4	E5	E6	E7	E8	E9
0.102	0.1023	0.129	0.129	0.102	0.129	0.129	0.0967	0.081

Tab. 12. Questionnaire response rate

Transport organisations / Type of the questionnaire response rate	JSC X transport	JSC X I subdivision	SIA B transport	SIA B I subdivision
Units	72	11	78	7
Percentages	82 %	100 %	100 %	100 %

Tab. 13. Distribution of the generalised estimate in the subdivisions of transport organisations by the SAW method

Organisations	SAW					Generalised estimate
	Estimates of explicit competencies' block	Normalised estimates	Estimates of tacit competencies' block	Normalised estimates	Sum of estimates	Normalised estimates
JSC X transport	151.49	0.17914	191.68	0.13619	343.17	0.31533
JSC X I subdivision	21.1	0.18751	44.51	0.24197	65.61	0.42947
SIA B Transport	31.95	0.20555	76.99	0.24934	108.94	0.45490
SIA B I subdivision	13.78	0.21561	31.56	0.25334	45.34	0.46895

Tab. 14. Estimates and their values

The scale of numeric estimates / Intervals	[0.13619; 0.17524)	[0.17524; 0.21429)	[0.21429; 0.25334]
The Scale of Linguistic Estimates	Low	Average	High
The estimates of explicit competence criteria in transport organisations falling into the interval		JSC X transport SIA B Transport JSC X I- subdivision	SIA B I subdivision
The estimates of tacit competence criteria in transport organisations falling into the interval	JSC X transport	-	JSC X I subdivision SIA B Transport SIA B I subdivision

Tab. 15. Measures to strengthen the competencies of logistics specialists

Group of explicit competencies	Measure
Use of information technologies (technically complex) in transportation	Learning by working Qualification development courses Methods for compensation of qualification development courses provided by the management
Evaluation of the specifications of vehicle control systems	
Knowledge of vehicle technical assistance standards	
Preparation of engineering documentation	
Maintaining technological infrastructure in the transport organisation	
Consultations provided	
Group of tacit competencies	**Measure**
Work complexity	Open communication Employee incentives (monetary and non-monetary) Applied training courses (not related to speciality)
Employee influence on the realisation of organisational goals	
Work culture	
Creativity	
Motivation to work	
Autonomy at work	

Determining the degree of compatibility of expert opinions. Verifying the compatibility of expert opinions is an obligatory step if a decision is made on their basis. It is highly recommended that the compatibility of all experts should be checked while using the SAW and AHP methods. The value of the concordance coefficient W approaches zero, i.e., W=0.0674. Therefore, experts were asked to fill out the tables once more. The concordance coefficient of the explicit competence block was equal to 0.4056 after completing the second compatibility calculation of expert opinions. This shows that expert opinions were in weak agreement; thus, a formula X^2 (Formula 13) was calculated additionally. The values of X^2_{kr} were used from the table according to the level of significance α (in practice, the value of α is 0.05 or 0.01) and the degree of freedom $v= m - 1$.

$$X^2=W\ r\ m\ (m-1) \qquad (13)$$

If the value X^2 calculated by the formula (13) is greater than X^2_{kr}, expert evaluations are in agreement. The first verification according to the selected level of significance α=0.05 with a degree of freedom ν=5 and $X^2_{kr}=11.07$, while $X^2 < X^2_{kr}$ showed that expert opinions were in agreement.

The calculated Kendall's coefficient of concordance did not identify the experts whose evaluations could differ. The coefficient of competence was calculated according to formulas (from 4 to 8). In this regard: $K_j^0 = \frac{1}{9} = 0.111$

The group estimates (Formula 5) and a new calculation matrix for the coefficient of competence were obtained. In order to calculate the final coefficients of competence based on Kendall, the sum of each row in the matrix was divided by lambda (Formula 6), which equals to 2089. It is important to note that the sum of the calculated estimates of the competencies should be equal to one. According to the analysis and results obtained from Table 11, it is possible to claim that experts 3, 4, 6 and 7 had the highest levels of competencies compared to other experts in the research.

The formula was used to check the competencies of all experts: $\overline{K}_i^t - 1.96s \leq K_i^t \leq \overline{K}_i^t + 1.96s$, $\overline{K}_i^t$ — the average of competence coefficient; s — the standard deviation and obtained intervals [0.013; 0.209]. The competence of the 9th expert was the lowest in this group (0.081) (Table 11). However, it was not as low as to eliminate this expert judgement from the research. Generally, it was possible to claim that experts with similar competence coefficients (0.129) held managerial positions for over five years. Notably, all experts had enough competencies to partake in the evaluation process.

Each subdivision of transport companies was presented with separate but identical questionnaires online. The questionnaire link was sent via email to each logistics specialist in the JSC X I subdivision, SIA B transport subdivision, and SIAB I subdivision. The questionnaire link for the JSC X transport was sent to a representative who forwarded the email to logistics specialists. The questionnaire response rate for JSC X I subdivision, SIA B and SIA B I subdivision was 100 %, while the JSC X transport had a response rate of 82 % (Table 12).

Normalised criteria estimates. The obtained data were normalised, and the generalised estimate was calculated for the competencies of the logistics specialists in each subdivision of transport organisations (Table 13).

The high estimates in the explicit competencies block show that logistics specialists have a substantial engineering competence in using information technologies (technically complex) in transportation. They can evaluate specifications of vehicle control systems and have a great understanding of vehicle technical assistance standards and engineering documentation, and maintain the technological infrastructure of the transport organisation. The low estimates indicate that managers should review the levels of education of all logistics specialists and provide opportunities to study, encourage the use of technologies and search for solutions to improve qualifications. The high estimates in the tacit competencies block show the great motivation to work, autonomy at work and initiative of a logistics specialist in achieving and realising the company's goals. Additionally, it shows the pursuit of high results by taking responsibility for one's actions and the ability to do complex work while complying with organisational culture. The low estimates in the tacit competencies block show that managers should draw their attention to the motivation of their employees and gather their team for joint activities, thus promoting communication. Also, pursuing objectives and initiatives is greatly important.

The step of interval estimation is calculated as a difference between the maximum and minimum estimate values divided by the number of intervals, i.e., the calculation is based on the formula:

$$h = \frac{x_{max} - x_{min}}{m} \quad (14)$$

here, h — the step of interval estimation, x_{max} — the highest criterion estimate, x_{min} — the lowest criterion estimate, m — the number of intervals.

$$h = \frac{0.25334 - 0.13619}{3} = 0.03905$$

Interval points t_n, n=1,2,3,…k are determined as follows:

$t_1 = x_{min}$, t_1=0.13619
$t_2 = t_1 + h$, t_2=0.13619+0.03905=0.17524
$t_3 = t_2 + h$,
…
$t_n = t_{n-1} + h <= x_{max}$

Thus, h=0.03905, and calculated intervals and their linguistics values are presented in Table 14.

The estimates for the group of tacit competencies in JSC X transport are rather low, signalling the issues of knowledge transfer, motivation, autonomy and cooperation between logistics specialists. The management staff of these transport organisations should focus on team-building and/or leadership to better use the potential of logistics specialists. This would encourage employee confidence and boost cooperation and motivation to collaborate. The lowest difference between tacit and explicit competencies groups can be detected only in the SIA B I subdivision. Logistics specialists in this subdivision have a substantial qualification in information technologies and their application in transportation. They can evaluate the specifications of vehicle control systems, have a great knowledge of vehicle technical assistance standards and may prepare engineering documentation. They monitor technological infrastructure in their transport organisation, continuously improve their qualifications, and pursue the goals and objectives of the transport organisation. These employees are autonomous, take responsibility for their decisions and are greatly motivated to work. The activities of logistics specialists in this organisation are organised properly. Thus, no performance-altering decisions should be implemented.

The evaluation of the competencies of logistics specialists provides information on the existing competencies and subsequently results in certain decisions and solutions for the effective management of such competencies. Upon completing the evaluation and reviewing the results of experimental research, it is purposeful to use the suggested measures to promote or upgrade the qualifications of logistics specialists (Table 15).

The competencies of logistics specialists in transport organisations fall into competence groups of the explicit and tacit categories. The multicriteria methodologies (SAW and AHP) were applied to evaluate the competencies of logistics specialists in transport organisations. The developed algorithm, consisting of four stages, may undergo the following corrections:

- while forming the expert group, alterations in the contents and number of the criteria are possible;
- changes in competence evaluation criteria are possible;
- changing competencies altogether is also possible;
- changing the scale of evaluations is possible.

Conclusions

The competencies of logistics specialists in transport organisations were classified into explicit and tacit competence groups. The developed methodology for evaluating competence criteria enabled a comprehensive evaluation and quantitative measuring of logistics specialists' competencies. The SAW methodology was used to determine the significances of the criteria, while a pairwise comparison was made using the AHP multicriteria methodology. Therefore, the analysis of the results provided opportunities for diverse and miscellaneous comparisons. Determining the most important competencies is an obligatory step for management staff to make decisions concerning employee qualification development, to encourage employees with extensive experience, and to strive for the best results.

The SAW methodology made it possible to objectively/scientifically evaluate the competencies of logistics specialists according to the selected criteria. The AHP method perfectly complements the SAW method — the competencies of logistics specialists are assessed by the pairwise method. Considering the existing competencies of logistics specialists, the result analysis of these methods enables managers to come up with reasonable decisions pertaining to qualification development and establishing an employee motivation system.

An expert evaluation of the competencies of logistics specialists determined that tacit competencies were more important for a logistics specialist. Consequently, experts prioritised organisational culture, motivation and autonomy in the workplace. The competencies "knowledge of vehicle technical assistance standards, motivation and autonomy at work" were of particular importance for a logistics specialist as they showed the relevance of engineering competencies for occupational duties performed by a logistics specialist.

The conducted experiment confirmed that the developed and standardised methodology to evaluate the competencies of logistics specialists in transport organisations is flexible, i.e., applicable in different transport organisations. An experiment in the selected subdivisions of transport companies determined that weak and strong competencies were highlighted. High estimates of tacit or explicit groups indicate that logistics specialists have a substantial number of competencies, and managers should simply monitor the situation. Average estimates of tacit or explicit groups show that managers should take a closer look at strengthening certain competencies. Low estimates of tacit or explicit groups mean that managers are obliged to take all the necessary steps and decisions to develop qualifications and apply corresponding measures.

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Leveraging lean and green supply chain practices for sustainable supply chain performance: the moderating role of environmental orientation

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ABSTRACT
This study investigates the impact of lean and green supply chain practices on business process performance and sustainable supply chain performance. The research utilises the resource-based view (RBV) theory to construct a conceptual model wherein lean and green supply chain practices are employed to augment business processes and sustainable performance. Concurrently, dynamic capabilities theory is applied to signify an organisation's capacity to adapt and evolve in response to internal and external pressures from customers and competitors. The conceptual model is validated using structural equation modelling with a sample of 170 supply chain practitioners from the apparel and textile supply chain in Jordan. Results indicate that lean practices exhibit no direct impact, whereas green practices significantly influence business process performance and indirectly affect sustainable supply chain performance. Business process performance does not mediate the relationship for lean practices, but it does so for green practices. Moreover, the environmental orientation of both competitors and customers negatively moderates the impact of green practices on business processes and sustainable supply chain performance. These findings contribute to existing literature and underscore the crucial role of green supply chain practices in enhancing sustainable supply chain performance in the apparel and textile industry.

KEY WORDS
lean, supply chain, green supply chain, business process performance, environmental orientation, sustainable, apparel industry, textile industry, Jordan

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Introduction

While the global apparel and textile (A&T) industry plays a critical role in the economy, it also faces substantial environmental and social challenges. The necessity for sustainable supply chain practices within this sector is evident, driven by the need to align with consumer and regulatory expectations while mitigating negative environmental and societal impacts. Achieving sustainable supply chain performance in this context requires the simultaneous adoption of lean and green supply chain practices.

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The combination of lean supply chain practices, centring on waste elimination and efficiency enhancement (Dora et al., 2016; Dhingra et al., 2014), and green supply chain practices, which incorporate environmental considerations into the supply chain (Razzak, 2022), is thought to yield the most effective outcomes for sustainable supply chain performance (Dües et al., 2013; Fercoq et al., 2016; Naseem & Abbas, 2022; Aladayleh et al., 2023).

Critical gaps persist, although the literature recognises the potential synergy between lean and green supply chain practices for achieving sustainable supply chain performance. Essaber et al. (2021) and Ezzahra et al. (2022) argue that there is a need for clarification regarding the relationship between lean and green paradigms, underscoring the importance of tangible integration approaches. Furthermore, comprehensive coverage of empirical research on the impact of these practices, particularly in the manufacturing sector, is yet to be attained (Kosasih et al., 2023; Lima et al., 2022).

Incorporating lean, green, and sustainability into the supply chain poses a formidable integration challenge, even for organisations in developed countries (Essaber et al., 2021; Ezzahra et al., 2022). Awan et al. (2022) emphasised the complexities that organisations encounter when attempting to merge lean, green, and sustainability approaches.

Numerous studies have explored the effects of either lean or green supply chains on sustainable performance. However, there is a need for additional research that investigates the integration of both models. Additionally, there is an apparent absence of studies examining the moderating role of environmental orientation in the relationship between lean and green supply chains, specifically in sustainable supply chain performance.

Kosasih et al. (2023) highlighted the need to investigate how lean and green practices influence the sustainable supply chain performance of manufacturing. Simultaneously, El-Garaihy et al. (2022) delved into institutional pressures and environmental orientation, emphasising their roles in implementing green supply chain practices and their considerable impact on economic and ecological performances. Khattab et al. (2022) stressed the importance of environmental orientation, particularly in adopting green supply chain practices. Furthermore, Choudhary et al. (2022) explored the effects of lean and quality management practices on green supply chain practices, revealing enhancements in operational and environmental performances despite the decrease in economic performance. Awan et al. (2022) contributed by demonstrating the substantial impact of lean manufacturing practices on sustainable performance and elucidating the mediating role of green supply chain management.

While current research suggests that a proactive environmental stance among competitors and heightened environmental awareness among consumers encourage adopting lean and green practices, there is still a notable gap. It is crucial to explicitly explore how the environmental orientation of both competitors and consumers influences the relationship between lean and green supply chain practices. A holistic approach is necessary to effectively implement lean and green practices, particularly within the apparel and textile (A&T) industry. The challenges associated with extending these practices to developing countries, especially in the textile sector, highlight significant gaps in existing research. Bridging these gaps is essential for a nuanced understanding of the interplay between lean and green supply chain practices and their impact on sustainable supply chain performance.

According to the World Trade Organisation (2021), International Labour Organisation (2021), and McKinsey & Company (2021), the apparel and textile (A&T) industry stands as a cornerstone in the global economy, wielding considerable economic value and employment influence. Engaged in the production of clothing, textiles, and related goods, this industry is a significant contributor to the economic growth of numerous nations. The World Trade Organisation (WTO) estimates the global textile and apparel industry's value to be an impressive USD 2.4 trillion, underscoring its substantial economic footprint. The A&T sector operates within intricate supply chains, with production typically concentrated in developing countries and consumption predominantly in developed nations. However, this industry grapples with multifaceted challenges, ranging from sustainability concerns and labour conditions to the rapid pace of technological advancements. As highlighted in reports by the International Labour Organisation (ILO) and McKinsey & Company, responsible business conduct and navigating the evolving landscape are pivotal for the A&T industry's sustainable development. Given its profound impact on the global economy, continuous scrutiny and analysis of this sector are imperative.

According to the Jordan Chamber of Industry and Jordan Investment Board, Jordan's Apparel and Textile (A&T) industry plays a significant role in the country's economy, substantially contributing to industrial exports. As the Jordan Investment Board reported, the A&T sector stands as Jordan's second-largest export sector, constituting approximately 20 % of total exports. The sector employs around 75,000 workers, predominantly in the garment-manufacturing sub-sector. The industry strongly emphasises export-oriented production, with a considerable portion directed towards the US and EU markets (Jum'a, 2023).

Moreover, the industry has benefited from several free trade agreements with the US and EU, increasing exports and attracting foreign investment. Renowned for its highly skilled workforce and the ability to manufacture high-quality products at competitive prices, the A&T industry faces challenges common to many industrial sectors, including the pressure on natural resources and contributions to pollution and waste (Al-Ma'aitah, 2018; Diab et al., 2015).

Beyond lean and green supply chain practices, environmental orientation is a critical factor influencing sustainable supply chain performance. Environmental orientation is an organisation's recognition and response to environmental considerations in operations and decision-making (Keszey, 2019). This orientation has shown a positive impact on Business Process Performance (Chan, 2010; Dolores López-Gamero et al., 2011), as well as overall financial and market performance (Leonidou et al., 2017; Amores-Salvadó et al., 2015; Vidal et al., 2022).

The environmental orientation of competitors and consumers can influence the impact of lean and green management practices on business process performance. Awan et al. (2022) emphasised the role of the environmental orientation of competitors and consumers in influencing the adoption and implementation of Green Supply Chain Management, suggesting that it can moderate the impact of lean management practices on business process performance. Choudhary et al. (2022) revealed that adopting lean and quality management practices led to improvements in operational and environmental performance. This underscores the notion that the environmental orientation of competitors and consumers, which may drive the adoption of green supply chain practices, can moderate the impact of lean management practices on business process performance.

Furthermore, Kosasih et al. (2023) emphasised the necessity for a practical model to encourage companies to adopt lean and green practices. This underscores the potential moderating influence of environmental orientation on the connection between lean and green practices and business process performance. El-Garaihy et al. (2022) highlighted the substantial impact of environmental orientation on green supply chain practices and their positive effects on economic and ecological performances.

However, the relationships among environmental orientation, lean supply chain practices, green supply chain practices, and sustainable supply chain performance require further clarification and investigation (Raut et al., 2021; Fercoq et al., 2016; Huo et al., 2017). This need is particularly pronounced in Jordan's Apparel and Textile (A&T) industry, where organisations aspire to achieve sustainable supply chain performance but need more specific models and approaches for success. This research aims to fill this gap by examining the relative impact of business process performance when implementing lean and green management practices in Jordan's A&T industry. Additionally, the study aims to test the moderating effect of environmental orientation on the relationship between green supply chain practices and business process performance, contributing to a deeper understanding of how business process performance, influenced by the lean and green approach, contributes to sustainable supply chain performance.

This research addresses gaps in the existing literature and the practical implementation of sustainable practices in the A&T industry, specifically focusing on extending these practices from developed to developing countries. The study is significant for the textile sector, providing valuable insights that can inform strategies for achieving sustainable supply chain performance in this critical industry.

The rest of this paper is organised as follows: Section 2 discusses the literature review and hypotheses development. Section 3 details the methodology, sampling, measures, and the survey. The measurement and structural model results are presented in Section 4. Section 5 discusses the results and provides theoretical and managerial implications. Finally, Section 6 offers a conclusion, limitations, and directions for future work.

1. Literature review and hypotheses development

In alignment with the resource-based view (RBV), organisations attain a competitive edge by efficiently leveraging and managing natural resources (Hart, 1995; Hart & Dowell, 2011). Extending this perspective, lean and green practices can be viewed as resources empowering organisations to enhance business process performance and sustainability (Awan et al., 2022; Waqas et al., 2022). The study's conceptual model is also congruent with dynamic capabilities defined by Teece et al. (1997) as an organisation's ability to adapt to external and internal pressures. Organisations can adeptly respond to the escalating market demand for sustainability by improving business process performance through lean and green practices.

Various lean manufacturing and green practices significantly influence sustainability performance, aligning with RBV theory's emphasis on internal resources and capabilities (Waqas et al., 2022). According to Waqas et al. (2022), sustainable firm performance is triggered by lean, green, and supply chain practices, underscoring the role of unique and valuable resources in driving sustainability. The integrated lean-green practices and supply chain sustainability for manufacturing underscores the necessity for a practical model to attract organisations to lean and green practices, in harmony with RBV theory's acknowledgement of the importance of developing and leveraging internal resources (Sukwadi & Caesar, 2022).

Supply chain sustainability involves integrating environmentally and socially responsible practices throughout the supply chain. This integration ensures that processes, products, and services contribute to the health and well-being of society and the environment (Espinoza et al., 2023; Keller et al., 2022). Sustainability in the supply chain has gained significant attention due to the increasing world population, resource scarcity, and the imperative to address environmental and social impacts (Espinoza et al., 2023).

Sustainable supply chain performance measures the environmental and social impacts of supply chain activities (Fercoq et al., 2016). Lean supply chain practices aim to minimise waste and improve efficiency in the supply chain (Kosasih et al., 2023), while green supply chain practices focus on reducing environmental impact (Choudhary et al., 2022). The sustainability performance in supply chain management underscores the need to adapt lean and green supply chains to contemporary manufacturing processes and environmental protection (Espinoza et al., 2023; Sharifpour et al., 2022).

Environmental orientation refers to business strategies and management approaches prioritising environmental sustainability. In this context, environmental orientation signifies a company's commitment to minimising environmental impact and integrating sustainability principles into its operations (Vidal et al., 2022; Kosasih et al., 2023; Azam et al., 2022). These concepts are interconnected and essential for creating a sustainable and efficient supply chain. They collectively address environmental and social impacts, efficiency, and governance mechanisms, all crucial for achieving long-term success while minimising environmental and social impacts.

Fig. 1 shows a proposed conceptual framework consisting of five factors: lean supply chain practices, green supply chain practices, business process performance, sustainable supply chain performance, and environmental orientation for competitors and customers. Business process performance mediates the relationship between lean and green supply chain practices in sustainable supply chain performance. The environmental orientation of competitors and customers moderates the relationship between green supply chain practices and business process performance.

1.1. Lean supply chain practices, business process performance, and sustainable supply chain performance

Lean supply chain practices are acknowledged in the literature for their positive influence on sustainable supply chain performance (Dora et al., 2014; Lyu et al., 2020; Jiang et al., 2018; Carter & Liane Easton, 2011; Lee & Zhang, 2019; Bhanot et al., 2017; Dües et al., 2013). The fundamental principle of the lean model revolves around fostering collaboration among interdependent partners, eliminating waste, and streamlining non-value processes through comprehensive value chain analysis (Dora et al., 2016). Critical implementations of lean supply chain practices, such as just-in-time, lead time reduction, and mass customisation, have effectively reduced waste and enhanced efficiency in companies (Jiang et al., 2018; Carter & Liane Easton, 2011; Lee & Zhang, 2019).

Furthermore, the lean model is crucial in identifying organisational gaps and standardising internal processes to achieve technical and organisational flexibility (Bhanot et al., 2017; Dües et al., 2013). The literature underscores that business process performance mediates the relationship between lean supply chain practices and sustainable supply chain performance (Raut et al., 2021; Fercoq et al., 2016; Amores-Salvadó et al., 2015). Implementing the lean model enhances business process performance and overall sustainability (Feng & Jiang, 2022). This is attributed to the lean model's focus on waste reduction, efficiency improvement, and subsequent enhancement of business process performance, ultimately culminating in improved sustainability performance (Raut et al., 2021; Fercoq et al., 2016; Huo et al., 2019).

The literature review suggests a positive impact of lean supply chain practices on sustainable supply chain performance and identifies business process performance as a mediating factor in this relationship. Given this, investigating the effects of lean supply chain practices on business process performance and sustainable supply chain performance in this specific industry is particularly relevant.

Based on the literature, the following hypotheses are formulated:

H1: Lean supply chain practices positively impact business process performance in the Jordanian A&T supply chain.

H2: Business process performance mediates the relationship between lean supply chain practices and sustainable supply chain performance in the Jordanian A&T supply chain.

1.2. Green supply chain practices, business process performance, and sustainable supply chain performance

Green supply chain practices encompass initiatives such as energy use reduction, eco-design, and waste management, which have been shown to enhance business process performance (Leonidou et al., 2017; Doolun et al., 2018; Feng & Jiang, 2022). Implementing optimal environmental practices, including adopting more efficient processes, eco-friendly packaging, emission reduction, and recycling, has been associated with achieving economic value and improving business process performance (Doolun et al., 2018; Lyu et al., 2020).

Moreover, the relationship between green supply chain practices and sustainable supply chain performance is mediated by business process performance. By augmenting business process performance through the adoption of green supply chain practices, companies are positioned to achieve superior sustainable supply chain performance outcomes (Raut et al., 2021; Fercoq et al., 2016; Amores-Salvadó et al., 2015). This is attributed to the focus of green supply chain practices on waste reduction and efficiency improvement, contributing to an enhanced business process performance that ultimately translates into improved sustainable supply chain performance (Huo et al., 2019).

The hypotheses proposed that green supply chain practices play a pivotal role in enhancing both business process performance and sustainable supply chain performance. Companies operating in this sector stand to improve their overall performance by prioritising green supply chain practices initiatives and recognising the mediating influence of business process performance on sustainable supply chain performance. Drawing from the reviewed literature, the following hypotheses are posited:

H3: Green supply chain practices positively impact business process performance in the Jordanian A&T supply chain.

H4: Business process performance mediates the relationship between green supply chain practices and sustainable supply chain performance in the Jordanian A&T supply chain.

1.3. Business process performance and sustainable supply chain performance

A thorough literature examination indicates that business process performance is critical to sustainable supply chain performance. Business process performance is integral to achieving sustainable outcomes (Raut et al., 2021). sustainable supply chain performance, in this context, refers to a supply chain's ability to meet present needs without compromising the ability of future generations to meet their own needs (Fercoq et al., 2016).

Empirical evidence supports the notion that the implementation of green supply chain practices, encompassing measures like energy use reduction, eco-design, and waste management, can enhance business process performance, ultimately contributing to improved sustainable supply chain performance (Leonidou et al., 2017; Doolun et al., 2018). Companies focusing on optimal environmental practices, such as adopting efficient processes, eco-friendly packaging, emission reduction, and recycling, can simultaneously achieve economic value (Doolun et al., 2018; Lyu et al., 2020). Additionally, lean supply chain practices have been identified as effective means to reduce waste and increase operational efficiency (Jiang et al., 2018; Carter & Liane Easton, 2011; Lee & Zhang, 2019).

Furthermore, existing research highlights that business process performance acts as a mediator in the relationship between green supply chain practices and sustainable supply chain performance (Raut et al., 2021; Fercoq et al., 2016; Amores-Salvadó et al., 2015). This implies that by enhancing business process performance by adopting lean and green supply chain practices, companies can achieve superior sustainable supply chain performance outcomes (Raut et al., 2021; Fercoq et al., 2016; Huo et al., 2019).

Given the robust support from the literature, the following hypothesis is well-founded and can be proposed:

H5: Business process performance positively impacts sustainable supply chain performance in the Jordanian A&T supply chain.

1.4. Moderating-mediating role of environmental orientation

The moderating role of environmental orientation has been extensively acknowledged in prior research (e.g., Jiang et al., 2018; You et al., 2019; Groening et al., 2018; Vidal et al., 2022). These studies highlight environmental orientation as a critical moderator influencing the relationship between green supply chain practices and performance, offering a comprehensive perspective on the impact of lean and green approaches on process performance and sustainability. Notably, two specific moderators, competitor environmental orientation and customer environmental orientation, are identified within the study model, contributing to a nuanced understanding of the moderation effects. Despite the valuable insights provided by external environment-related moderator variables, they are, regrettably, "seldom considered".

Competitor and customer environmental orientation, assessed as micro-environmental variables, are defined by the degree to which competitors and customers perceive environmental issues as significant (Dolores López-Gamero et al., 2011; Chan, 2010; Sharafuddin, 2022). This study posits that these factors can moderate the relationship between green supply chain practices and business process performance. In markets with high competitors and customer environmental orientation, customers strongly prefer environmentally friendly products, and competitors actively emphasise green values (Leonidou et al., 2013). In such environments, survival necessitates companies to be attuned to customer preferences and competitor actions (Dolores López-Gamero et al., 2011; Vidal et al., 2022). Consequently, under heightened environmental pressure from competitors and customers, environmental orientation is expected to amplify its impact on business process performance, indirectly influencing sustainable performance (Leonidou et al., 2013).

Facing elevated environmental pressure, firms are incentivised to develop effective environmental marketing strategies, navigating market turbulence and managerial uncertainty (Fraj-Andrés et al., 2009; Mastos et al., 2022). The ensuing uncertainty prompts firms to leverage intangible resources efficiently. Thus, given the higher pressure levels from the microenvironment, we anticipate that environmental orientation will exert a more pronounced impact on green supply chain practices when both competitors and customers exhibit a heightened environmental orientation. In competitive environments, adopting environmental strategies gives firms a substantial advantage over rivals that is challenging to negate.

Likewise, environmentally conscious customers are inclined to avoid products that are not produced sustainably. Consequently, under conditions of high customer environmental orientation, it is posited that firms more actively engaged in green supply chain practices will exhibit superior processes (Dolores López-Gamero et al., 2011; Vidal et al., 2022; Chavez et al., 2022). The environmental orientation, conceptualised as a second-order model, leads to the formulation of moderator relationships as follows:

H6: The impact of green supply chain practices on business process performance in the A&T supply chain is moderated by the environmental orientation of both competitors and customers.

1.5. Moderating role of environmental orientation on the relationship between green supply chain practices and business process performance and sustainable supply chain performance

Considering (Jiang et al. 2018; You et al., 2019; Groening et al., 2018; Vidal et al., 2022), this study proposes a nuanced perspective on the moderating role of environmental orientation in the relationship between green supply chain practices and business performance and sustainable supply chain performance.

Environmental orientation, as gauged from the standpoint of competitors and customers, emerges as a pivotal factor in shaping the impact of green supply chain practices on business process performance and sustainable supply chain performance. The environmental consciousness of competitors and customers, reflecting their perception of environmental issues' importance (Dolores López-Gamero et al., 2011;

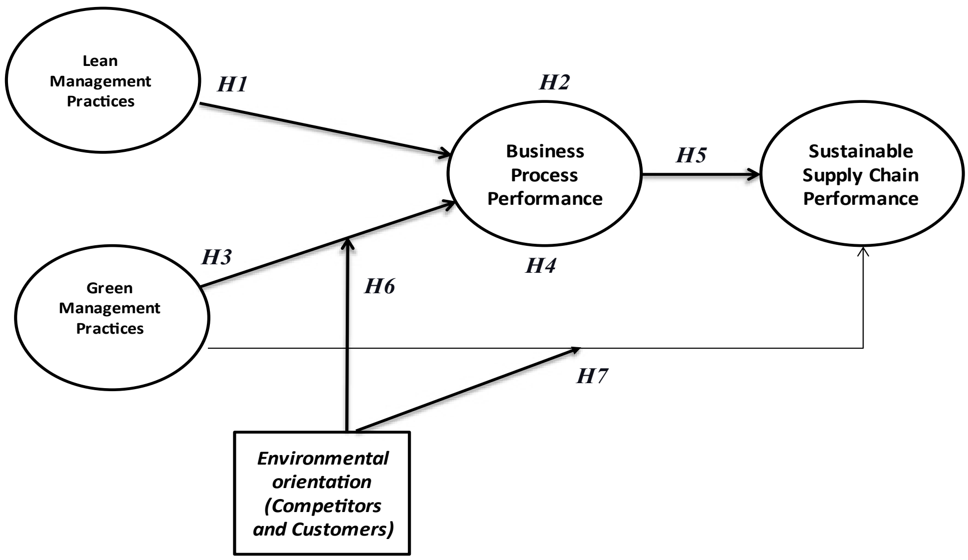

Fig. 1. Proposed Conceptual Framework

Chan, 2010; Sharafuddin, 2022), stands out as a key moderating variable.

In markets characterised by high-end customers and competitor environmental orientation, a distinctive consumer preference exists for environmentally friendly products and a concerted effort by competitors to underscore green values (Leonidou et al., 2013). Navigating such markets necessitates companies to be attuned to customer preferences and competitor actions to thrive (Dolores López-Gamero et al., 2011; Vidal et al., 2022). Consequently, the environmental orientation of competitors and customers is posited to amplify the influence of green supply chain practices on both business process performance and sustainable supply chain performance (Leonidou L.C. et al., 2013).

Furthermore, heightened market pressure from the micro-environment towards environmental values introduces managerial uncertainty and turbulence (Fraj-Andrés et al., 2009; Mastos et al., 2022). This uncertainty, in turn, may affect firms' efficient utilisation of intangible resources. In environments where both competitors and customers are more environmentally oriented, the environmental orientation is anticipated to exert a more pronounced impact on green supply chain practices. Embracing environmental strategies in competitive settings becomes instrumental for firms to gain a substantial edge over key rivals (Dolores López-Gamero et al., 2011; Vidal et al., 2022). Similarly, environmentally conscious customers will likely abstain from purchasing products that do not adhere to sustainable production practices. Consequently, under high competitors and customer environmental orientation conditions, a positive relationship is anticipated between the firm's engagement in green supply chain practices and both process efficiency and sustainable performance (Chavez et al., 2022).

Building on this rationale, the following hypothesis is posited:

H7: Environmental orientation of competitors and customers positively moderates the effect of green management practices on business process performance and sustainable supply chain performance.

Fig. 1 illustrates the conceptual model of this study.

2. Methodology

2.1. Measures, survey, and methods

This study aims to examine and substantiate the impact of lean supply chain practices and green supply chain practices on business performance and sustainable supply chain performance within the A&T supply chain in Jordan. Additionally, the study endeavours to validate the moderating role of environmental orientation from competitors and customers in influencing the relationship between green supply chain practices, business process performance and sustainable supply chain performance. The research objectives were pursued by analysing data collected from Supply Chain managers in the Jordanian A&T supply chains.

The data collection instrument was a questionnaire featuring individual items gathered from prior studies (refer to Appendix A for a comprehensive list of constructs and their items). Twelve items, drawn from the works of Fercoq et al. (2016), Raut et al. (2021), Dey et al. (2019), and Digalwar et al. (2020), were employed to gauge lean supply chain practices. The measurement of green supply chain practices adopted items from studies conducted by Huo and Wang (2019), Kumar and Rodrigues (2018), Lee et al. (2012), and Lee et al. (2015). Business process performance was measured using items derived from research by Lyons et al. (2019), Wan et al. (2014), and Zhang et al. (2007). The scale items for sustainable supply chain performance were developed based on studies by Raut et al. (2021) and Centobelli et al. (2020). Finally, items from the studies of Keszey (2019), Jiang et al. (2018), and Dolores López-Gamero et al. (2011) were employed to measure the environmental orientation of both competitors and customers.

The environmental orientation was modelled as a second-order construct, encompassing two sub-constructs: competitors and customers. All items were assessed using a five-point Likert scale (ranging from five for "Strongly Agree" to one for "Strongly Disagree"). A non-probability sampling method was used due to the absence of specific data from the A&T supply chains and the complexity of determining the number of managers involved in supply chain activities in industrial companies. The questionnaires were distributed to managers overseeing various aspects of supply chain operations, including purchasing, inventory, production, customer and supplier relations, and managers and engineers affiliated with companies engaged in supply chain operations within the Jordanian A&T sector.

The survey was meticulously designed to focus on individuals with expertise in manufacturing-related practices within the Jordanian A&T sector. Factories with a workforce exceeding 100 employees were deliberately selected to ensure a comprehensive and representative sample — this criterion aimed to obtain a sufficiently large and diverse dataset.

In the distribution phase, the questionnaire was directly administered to managers identified through the research team. A targeted outreach effort targeted 230 managers across various companies within the sector. In total, 179 responses were received, reflecting the engagement and cooperation of the surveyed entities. Notably, 170 of these responses proved to be valid and substantial, contributing valuable information to the analysis. This subset constituted a significant 74 % of the total questionnaires received, attesting to the robustness and reliability of the collected data for the research objectives.

To counteract potential common method bias, the study followed the guidelines outlined by Podsakoff et al. (2003), urging respondents to finalise the questionnaire within a defined and brief timeframe (limited to a maximum of two weeks). The assessment of common method bias, conducted through Harman's single-factor test, revealed a variance of 37.06, well below the critical threshold of 50 %. This outcome affirms the absence of common method bias in the study.

The study employed partial least squares-structural equation modelling (PLS-SEM) using Smart-PLS to test the proposed model. PLS-SEM was deemed suitable for its capability to accurately estimate the relationships between constructs and simultaneously analyse structural and measurement models, especially in cases involving exploratory and intricate relationship models with elements of mediation and moderation (Chin, 1998; Sarstedt et al., 2017; Hair et al., 2014).

2.2. Sample

Table 1 presents comprehensive information on the study participants, offering insights into their demographics based on experience level, education, and job title. The breakdown of respondents by experience reveals that the largest segment (28 %) has less than five years of experience, followed by those with 5–10 years (22 %), 10-15 years (31 %), and over 15 years (19 %) of experience. Regarding educational background, the majority (55 %) hold an undergraduate degree, while 45 % possess a graduate degree.

The distribution of respondents across various job titles is as follows: 22 % in purchasing, 6 % in inventory, 8 % in production and operations, 7 % in customer relations, 14 % in supplier relations, 12 % in quality management, 7 % in design and engineering, 11 % in transportation and logistics, 5 % in information and technology, 2 % in marketing and sales, and 4 % in other roles.

Tab. 1. Information about the respondents

Experience	Frequency	%
Demographics		
< 5 Years	47	28 %
5 - < 10 Years	38	22 %
10 - < 15 Years	52	31 %
> 15 Years	33	19 %
Education		
Undergraduate	94	55 %
Graduate	76	45 %
Job title		
Purchasing	38	22 %
Inventory	11	6 %
Production and operations	14	8 %
Customer relations	12	7 %
Supplier relations	23	14 %
Quality management	21	12 %
Design and engineering	12	7 %
Transportation and logistics	19	11 %
Information and technology	9	5 %
Marketing and sales	4	2 %
Others (SC planners, analysts, project managers, export/import, auditors, etc.)	7	4 %
Total	170	

3. Results

3.1. Measurement model, reliability, and validity

Reliability signifies the extent to which the measurement model is devoid of error and consistently produces reliable results. Hair et al. (2014) advocate using Cronbach's alpha and composite reliability to assess reliability. A measurement model is deemed to yield consistent results when all alpha measures surpass the threshold of 70 %, and all composite reliability values are greater than 70 %. These criteria indicate that the measurement model provides reliable and dependable outcomes.

Validity, on the other hand, reflects the accuracy with which the items measure the intended construct. It is established when the Average Variance Extracted (AVE) values surpass the designated threshold of 0.5 (Fornell & Larcker, 1981), as illustrated in Table 2. Convergent validity, as indicated by Hair et al. (2014), is confirmed when standardised loading values for each item exceed the 0.70 cutoff (t-value > 2) and are statistically significant. The validity outcomes of the scale were enhanced by eliminating items with insufficient factor loadings, specifically those falling below the threshold of 0.70. A detailed presentation of these adjustments can be found in Appendix A, illustrating the items dropped from the analysis.

According to Hair et al. (2014), reliability is affirmed by assessing collinearity. As depicted in Table 2, the Variance Inflation Factor (VIF) values do not exceed the threshold value of three, indicating the absence of collinearity issues. This supports the formative nature of all constructs. The evaluation of the second-order measurement scale is also presented in Table 3.

Moreover, Table 3 highlights that the outer weights of each Environmental Orientation (EO) indicator surpass the 10 % limit, and the significant values of these weights for all indicators provide empirical support for the validity of the retained items. The results in Table 3 indicate positive relationships between the competitor's environmental orientation and the customer's environmental orientation with environmental orientation. Specifically, the competitor's environmental orientation exhibits the most significant contribution (0.551), followed by the customer's environmental orientation (0.529).

Discriminant validity gauges the degree to which a construct distinguishes itself from others. This is determined by calculating the square root of the AVE value for each construct and comparing it with the cross-loading values of different constructs (Fornell & Larcker, 1981). Considering these criteria ensures a comprehensive assessment of the measurement model's reliability and validity.

In Table 4, the results reveal that each construct's square root of the Average Variance Extracted (AVE) values surpasses the correlations in both rows and columns within the matrix. This finding suggests the achievement of discriminant validity. The first-order measurement model is characterised by reliability, internal consistency, and satisfactory convergent and discriminant validity levels.

Additionally, the cross-loading results indicate that values correlating with a particular variable are higher than those correlating with other variables. Consequently, the inter-variable correlation is low, indicating favourable conditions, and the discriminant validity values are within acceptable ranges, as detailed in Table 5.

Finally, Fig. 2 presents the outcomes of the measurement model testing, providing a visual representation of the results.

Tab. 2. First-order model

Constructs	Loading	VIF	A	CR	AVE
Business Process Performance			0.893	0.916	0.61
BPP1	0.720	1.666			
BPP2	0.757	2.095			
BPP3	0.798	2.281			
BPP4	0.798	2.663			
BPP6	0.821	2.301			
BPP7	0.788	2.729			
BPP8	0.781	2.513			
Competitors' environmental orientation			0.864	0.907	0.71
CEO1	0.817	1.909			
CEO2	0.828	2.120			
CEO3	0.863	2.414			
CEO4	0.862	2.237			
Customers' environmental orientation			0.822	0.883	0.655
CuEO1	0.708	1.359			
CuEO2	0.836	2.035			
CuEO3	0.827	1.931			
CuEO4	0.859	2.132			
Green supply chain practices			0.848	0.892	0.622
GP1	0.748	1.569			
GP2	0.811	2.115			
GP3	0.790	2.022			
GP4	0.800	1.901			
GP5	0.793	1.913			
Lean supply chain practices			0.889	0.913	0.599
LP10	0.751	2.083			
LP11	0.814	2.667			
LP12	0.804	2.173			
LP4	0.719	1.724			
LP5	0.786	2.017			
LP8	0.771	2.078			
LP9	0.771	2.335			
SSCP			0.819	0.88	0.647
SSCP2	0.808	1.678			
SSCP3	0.805	1.824			
SSCP4	0.803	1.835			
SSCP6	0.802	1.746			
α= Cronbach's Alpha; CR=Composite Reliability; AVE = Average Variance Extracted.					

Tab. 3. Second-order model evaluation (environmental orientation)

Second-order/ First-order constructs	Outer Variance Inflation Factors (VIF)	Outer Weights	Standard Deviation	T-value	P-values
Competitors' environmental orientation		0.551	0.02	28.185	0.000
CEO1	2.256	0.168			
CEO2	2.154	0.148			
CEO3	2.597	0.161			
CEO4	2.651	0.178			
Customers' environmental orientation		0.529	0.022	24.026	0.000
CuEO1	1.814	0.156			
CuEO2	2.223	0.161			
CuEO3	2.146	0.166			
CuEO4	2.195	0.17			

Tab. 4. Fornell–Larcker criterion of Discriminant validity for the first-order factor model

Construct	1	2	3	4	5	6
1. Business Process Performance	**0.781**					
2. Competitors' environmental orientation	0.670	**0.843**				
3. Customers' environmental orientation	0.746	0.716	**0.809**			
4. Green SC	0.714	0.486	0.613	**0.789**		
5. Lean SC	0.614	0.549	0.572	0.746	**0.774**	
6. Sust. SC performance	0.754	0.773	0.741	0.626	0.566	**0.805**

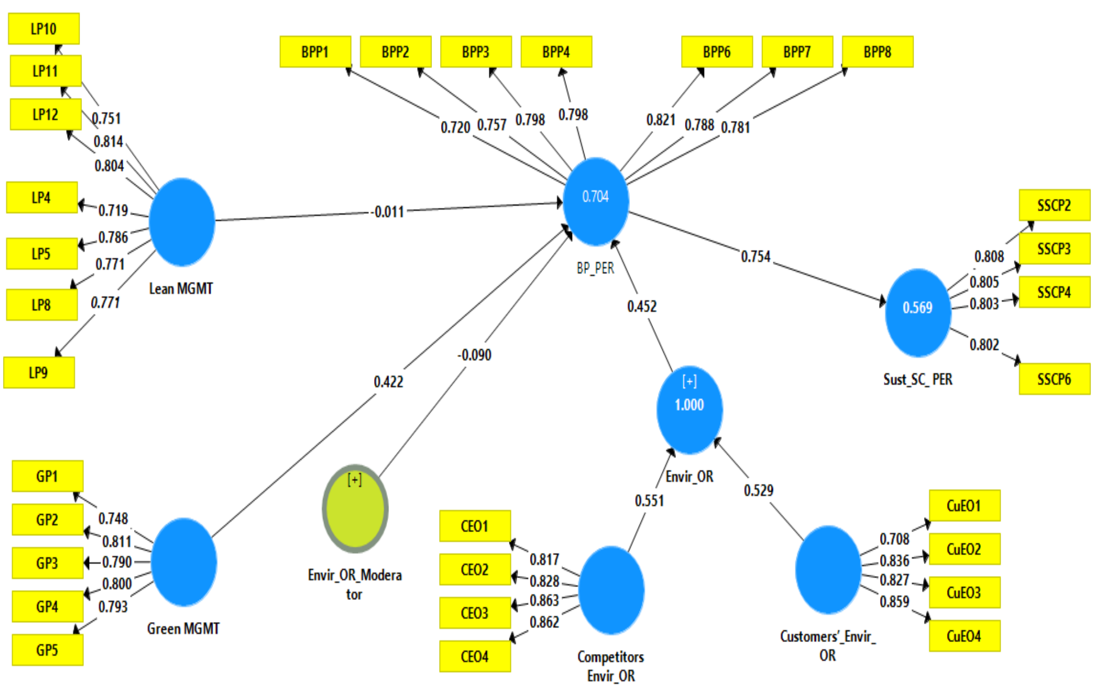

Fig. 2. Measurement scale output

Tab. 5. Fornell–Larcker criterion of discriminant validity for the first-order factor model

	Business Process Performance	Competitors' environmental orientation	Customers' environmental orientation	Green SC	Lean SC	Sust. SC performance
BPP1	**0.720**	0.378	0.523	0.670	0.550	0.491
BPP2	**0.757**	0.498	0.482	0.489	0.461	0.526
BPP3	**0.798**	0.551	0.613	0.530	0.505	0.543
BPP4	**0.798**	0.556	0.551	0.535	0.430	0.507
BPP6	**0.821**	0.604	0.674	0.573	0.444	0.645
BPP7	**0.788**	0.550	0.608	0.545	0.483	0.715
BPP8	**0.781**	0.508	0.604	0.565	0.493	0.658
CEO1	0.629	**0.817**	0.587	0.439	0.472	0.726
CEO2	0.478	**0.828**	0.520	0.338	0.397	0.604
CEO3	0.518	**0.863**	0.610	0.355	0.432	0.608
CEO4	0.628	**0.862**	0.685	0.497	0.540	0.667
CuEO1	0.580	0.614	**0.708**	0.387	0.405	0.513
CuEO2	0.596	0.529	**0.836**	0.458	0.391	0.580
CuEO3	0.605	0.593	**0.827**	0.609	0.584	0.674
CuEO4	0.631	0.579	**0.859**	0.522	0.464	0.624
GP1	0.568	0.472	0.531	**0.748**	0.718	0.558
GP2	0.562	0.401	0.504	**0.811**	0.528	0.529
GP3	0.503	0.286	0.363	**0.790**	0.545	0.409
GP4	0.603	0.360	0.512	**0.800**	0.561	0.478
GP5	0.568	0.386	0.492	**0.793**	0.584	0.485
LP10	0.393	0.355	0.386	0.531	**0.751**	0.332
LP11	0.492	0.408	0.470	0.582	**0.814**	0.422
LP12	0.507	0.518	0.474	0.549	**0.804**	0.492
LP4	0.406	0.381	0.427	0.566	**0.719**	0.362
LP5	0.558	0.466	0.505	0.590	**0.786**	0.522
LP8	0.478	0.426	0.408	0.658	**0.771**	0.469
LP9	0.460	0.396	0.410	0.565	**0.771**	0.431
SSCP2	0.685	0.576	0.682	0.631	0.563	**0.808**
SSCP3	0.542	0.673	0.585	0.396	0.386	**0.805**
SSCP4	0.557	0.609	0.544	0.445	0.376	**0.803**
SSCP6	0.624	0.640	0.559	0.510	0.471	**0.802**

3.2. Structural model and hypothesis testing

This study used structural equation modelling to examine relationships (Fig. 3). The findings presented in Table 6 indicate that all direct hypotheses are substantiated, except for the impact of lean supply chain practices (H1) on business process performance (β = -0.011, p= 0.89). The hypothesis regarding the influence of green SC practices (H3) on business process performance is confirmed (β = 0.422, p= 0.000), as is the effect of business process performance on sustainable supply chain performance (H5) (β = 0.754, p= 0.000). Following the procedures outlined by Preacher and Hayes (2008), bootstrapping was employed to assess mediation relationships, as detailed in Table 7.

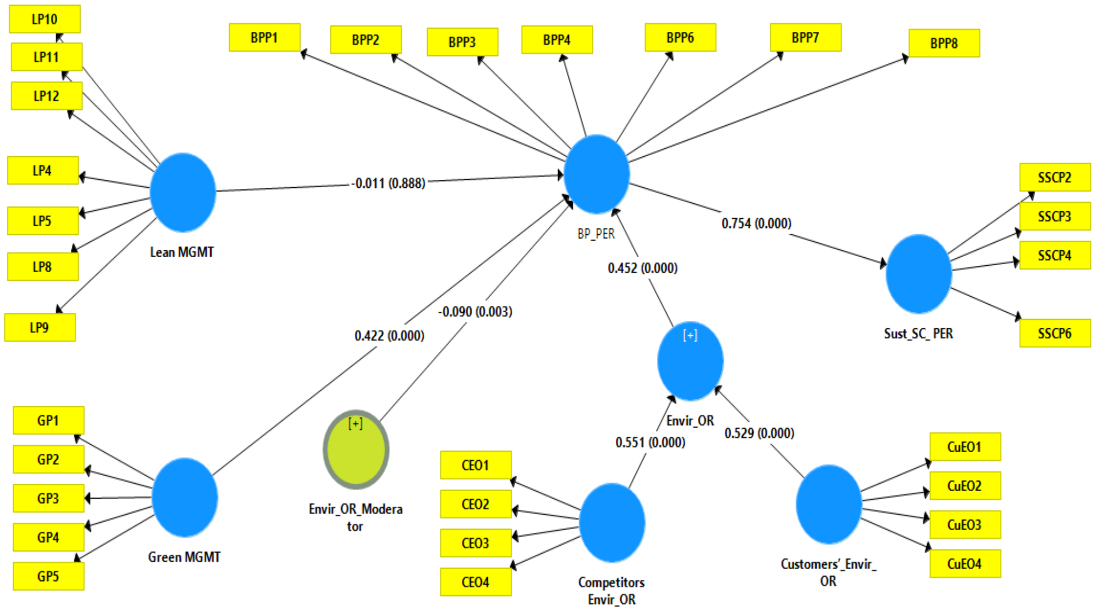

Fig. 3. Testing of the structural model

Tab. 6. Direct Hypotheses Testing

Hypothesis		Beta	Mean (M)	Standard Deviation (STDEV)	T (O/STDEV|)	P Values	Decision
Direct (H1)	Lean SC -> business process performance	-0.011	-0.005	0.082	0.138	0.890	Not supported
Direct (H3)	Green SC -> business process performance	0.422	0.424	0.067	6.313	0.000	Supported
Direct (H5)	Business process performance -> Sust. SC performance	0.754	0.756	0.052	14.564	0.000	Supported

Tab. 7. Indirect Hypotheses and moderated mediation analysis

Hypotheses (Path)		Estimate	Mean (M)	Standard Deviation (STDEV)	T (O/STDEV)	P Values	LL	UL	Decision
Indirect (H2)	Lean SC -> business process performance -> Sust. SC performance	-0.009	-0.003	0.062	0.138	0.890	-0.123	0.12	Not supported
Indirect (H4)	Green SC -> business process performance -> Sust. SC performance	0.318	0.32	0.049	6.513	0.000	0.227	0.417	Supported
*Confidence interval (CI): 95 % adopted									

The results reveal a significant and indirect effect of green supply chain practices on sustainable supply chain performance, mediated through business process performance (β = 0.318, t = 6.513, 95 % CI = 0.227, 0.417, and non-crossing zero). Meanwhile, the indirect effect of lean supply chain practices on sustainable supply chain performance, mediated by business process performance, is deemed insignificant (β = -0.009, t = 0.138, 95 % CI = -0.123 - 0.12, crossing zero). Consequently, the hypothesis regarding the indirect impact of green supply chain practices (H4) is supported, while the corresponding lean supply chain practices (H2) hypothesis is not supported.

3.3. Moderation-mediation analysis

The study also implemented Preacher and Hayes's (2008) procedures to examine moderation mediation further. Table 8 displays results indicating the attainment of formative factors in the second-order model of environmental orientation, specifically, competitors' environmental orientation (β = 0.551, P = 0.000) and customers' environmental orientation (β = 0.529, P = 0.000). Independently, the direct effect of environmental orientation on business process performance is statistically significant (β = 0.452, t = 6.013, P = 0.000). Furthermore, the moderation effect of environmental orientation on business processes, with green supply chain practices as an independent variable, is significant (β = -0.09, t = 2.891, P = 0.004).

Both the direct impact of green supply chain practices on business process performance (β = 0.422, p = 0.000) and the indirect effect of green supply chain practices on sustainable supply chain performance is significant (β = 0.318, t = 6.513, 95 % CI = 0.227, 0.417, not crossing zero). Consequently, the impact of environmental orientation on business process performance is negatively significant but small. Similarly, for the impact of environmental orientation as a moderation variable on the indirect path (green supply chain practices — business process performance — sustainable supply chain performance, the path test results indicate significance (β = -0.068, t = 2.88, 95 % CI = -0.14, (-) 0.417, not crossing zero). Thus, it can be concluded that the moderation mediation of the environmental orientation hypothesis (H6 and H7) is supported.

Table 8 presents the results of the moderated mediating analysis focusing on environmental orientation. The results indicate a significant negative direct moderation effect of environmental orientation on business process performance. The T-value of 2.891 and the associated p-value of 0.003 suggest that the relationship is statistically significant. The confidence interval (CI) further supports this, providing a range of values within which the actual effect is likely to lie. The moderation effect is negative, indicating that external factors influence the impact of environmental orientation on business process performance. Results in Table 8 also reveal a significant negative indirect moderation effect of environmental orientation on sustainable supply chain performance through business process performance. The T-value of 2.88 and the associated p-value of 0.000 indicate statistical significance. The confidence interval (CI) again supports the result, confirming that the media-

Tab. 8. Results of moderated mediating analysis of environmental orientation

Hypothesis		Beta	Mean (M)	Standard Deviation (STDEV)	T (O/STDEV|)	P Values	LL	UL	Decision
Direct moderation (interaction) H6	Environmental orientation (moderator)-> business process performance	-0.09	-0.09	0.031	2.891	0.003	0.161	0.329	supported
Indirect moderation (interaction) H7	Environmental orientation (moderator) -> business process performance -> sust. SC performance	-0.068	-0.07	0.024	2.88	0.000	-0.14	-0.01	Supported
*Confidence interval (CI): 95 % adopted									

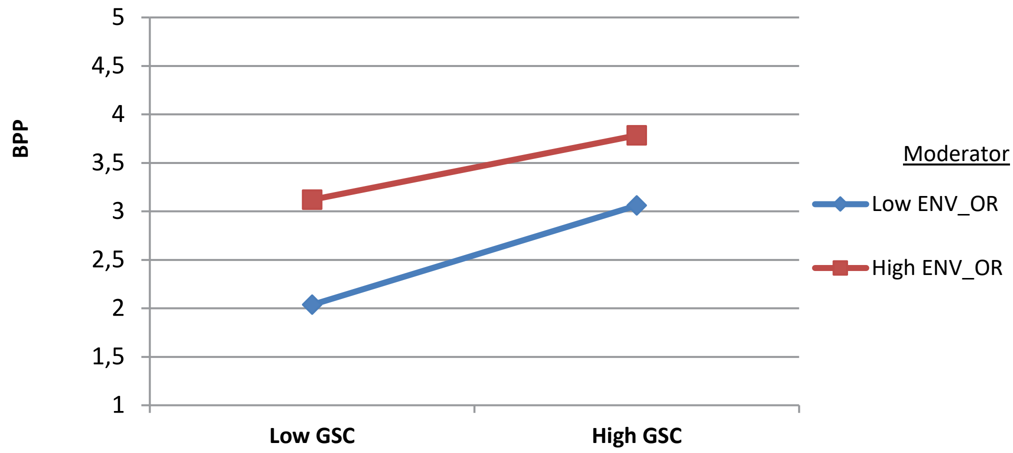

Fig. 4. Moderation effect of environmental orientation on green supply chain practices and business process performance

tion effect is likely present. This suggests that the influence of environmental orientation on sustainable supply chain performance is partially mediated by its impact on business process performance.

Results indicated that both direct and indirect moderation effects are supported by the analysis, indicating that environmental orientation plays a significant role in influencing both business process performance and sustainable supply chain performance. The results provide valuable insights into the complex interplay of these variables within the study context.

As illustrated in Fig. 4, the environmental orientation of competitors and customers underscores the relationship between green supply chain practices and business process performance. The results indicate that environmental orientation dampens the positive relationship between green supply chain practices and business process performance.

4. Discussion and theoretical and managerial implications

This paper examines the impact of green supply chain practices and lean supply chain practices on business performance and sustainable supply chain performance in industrial supply chains. Simultaneously, it explores the moderating role of competitors and customers' environmental orientation on the relationships between green supply chain practices, business process performance, and sustainable supply chain performance. The study employs a structural equation modelling approach to validate and ensure the reliability of the measurement model within the Jordanian A&T supply chain. It scrutinises the structural model and assesses the moderating effect.

The results do not provide direct support for the impact of lean supply chain practices on business process performance, and lean supply chain practices do not exert an indirect impact on sustainable supply chain performance. Conversely, the impact of green supply chain practices is highly significant on business process performance, and the indirect impact is also noteworthy.

Non-confirmation of the hypothesis regarding the impact of lean supply chain practices on business process performance and sustainable performance contradicts the findings of most studies (e.g., Razzak, 2022; Lee & Zhang, 2019; Naseem & Abbas, 2022). Several studies have illustrated the negative effects of lean supply chain practices on sustainable supply chain performance (e.g., D'Souza et al., 2020; Fikar et al., 2018). Despite A&T companies in Jordan adopting lean supply chain practices in their supply chains, they are still in the early stages of implementation. Further skills and experience are needed, such as managers in industrial companies with the ability to recognise the use of lean supply chain practices to enhance business process performance.

Companies require enhanced internal processes for material efficiency, including improved control and monitoring systems and inventory control systems that address removing materials or outdated products. A&T companies should also make more informed choices when selecting production locations to minimise packaging usage, especially for items exported overseas. Additionally, there is a need for more policies promoting recycling and reducing transportation costs, and there is a lack of emphasis on utilising reusable packaging or implementing inventory or just-in-time production strategies to minimise waste.

On the contrary, the results supported the hypothesis regarding the impact of green supply chain practices on both business performance and sustainable supply chain performance. This outcome aligns with the prevailing theoretical literature on green supply chain practices (Vidal et al., 2022; Mastos et al., 2022). Managers underscored that companies within the Jordanian A&T industry actively strive to integrate environmental considerations into their business practices, primarily through collaboration with suppliers and partners in their supply chains.

Industrial textile companies, in particular, are adopting sustainable design and production techniques while simultaneously undertaking measures to curtail their environmental footprint. These measures encompass minimising material usage, reducing energy consumption, and incorporating more environmentally friendly materials. Notably, efforts extend to decreasing energy consumption in distribution, recycling used and defective products, and collaborating with partners to appropriately manage industrial waste, including sewage, gas, solid, and liquid waste.

This proactive response to global pressures for reducing air emissions, curbing pollution, and conserving natural resources underscores a company's commitment to environmental sustainability intricately linked to its overall business strategy and sustainable performance (Chavez et al., 2022; Kosasih et al., 2023).

It has been observed that the perceptions of competitors and customers regarding the environment significantly impact a business's performance. This finding aligns with several studies (e.g., Amores-Salvadó et al., 2015; Sharafuddin, 2022). Markets with a robust environmental focus have customers who strongly prefer environmentally friendly products, and competitors prioritise green values and sustainability.

Contrastingly, the moderation effect of environmental orientation on the relationship between green supply chain practices and business performance, as well as on Sustainable Supply Chain Performance, is adverse but noteworthy. As depicted in Fig. 4, the moderation effect is subtle, indicating that environmental orientation restrains the positive correlation between green supply chain practices, business process performance, and sustainable supply chain performance. This result contradicts most studies emphasising that environmental orientation can positively influence green supply chain practices to enhance business performance and sustainable supply chain performance (Fraj-Andrés et al., 2009; Mastos et al., 2022).

The significant effect suggests that companies in the A&T supply chain are attuned to customer preferences and competitors' reactions, exerting precise environmental pressure on the companies' green values. However, concurrently, this dynamic creates uncertainty and managerial turmoil. This aligns with the perspectives of Vidal et al. (2022) and Leonidou et al. (2013), who argue that such uncertainty contributes to current situations remaining ambiguous concerning how companies utilise their resources.

Mastos et al. (2022) corroborate that heightened pressure from competitors, customers, or the overall microenvironment, particularly in design, production, distribution, and environmental delivery, may have adverse short-term effects on process performance and, consequently, sustainable performance. Faced with environmental pressures from competitors and customers, companies must make substantial short-term investments in intricate, environmentally friendly design. This involves significant expenditures in research and development, engineering design modifications, and diverse component processing costs. Such circumstances necessitate increased allocations for quality control and technology investment. These factors collectively lead to elevated costs, a decline in operational performance, and potential damage to market share and competitive advantage. Operational delays may arise due to changes in environmental policies (Chavez et al., 2022; Leonidou et al., 2013).

Research by various authors (e.g., Fraj-Andrés et al., 2009; Mastos et al., 2022; Vidal et al., 2022; Chavez et al., 2022) demonstrates that the adoption of environmentally conscious practices can confer a competitive advantage to businesses. Moreover, the substantial consumer demand for eco-friendly products is a significant motivator for companies to integrate sustainable production methods, leading to improved business outcomes and sustainable supply chain practices.

The finding that the environmental orientation of competitors and customers exerts a negative moderation effect on the influence of green supply chain practices on business performance and sustainable supply chain performance is a somewhat novel finding that merits further investigation. This insight suggests that the efficacy of green supply chain practices could be enhanced when operating in a market with low environmental awareness among competitors and customers.

However, this negative moderation effect might arise because companies facing heightened environmental orientation levels among their competitors and customers experience significant pressure to adopt green supply chain practices. Consequently, they witness a more substantial improvement in both business process performance and sustainability. In contrast, companies operating in a market with low environmental awareness among competitors and customers may encounter less pressure to adopt green supply chain practices, leading to a more modest enhancement in business process performance and sustainability. This nuanced dynamic highlights the intricate relationship between environmental orientation, green supply chain practices, and the environmental consciousness of the market, warranting in-depth exploration.

4.1. Theoretical implications

The theoretical implications derived from the hypothesis testing results in the A&T industry shed light on the effectiveness of green supply chain practices in enhancing business performance and contributing to heightened sustainability performance. This alignment with the principles of the natural resource-based view (RBV) theory is notable, as the RBV suggests that organisations gaining a competitive advantage effectively utilise and possess valuable resources (Hart, 1995; Hart & Dowell, 2011; Waqas et al., 2022). In the context of the A&T industry, green supply chain practices emerge as a crucial natural resource, empowering organisations to elevate their business process performance and sustainability performance.

Moreover, the results unveil a positive mediating role of business process in the relationship between green supply chain practices and Sustainable Supply chain performance (sustainable supply chain performance). This finding resonates with the concept of dynamic capabilities, denoting an organisation's capacity to adapt and evolve in response to internal and external pressures (Teece et al., 1997). By enhancing business process performance through the implementation of green supply chain practices, A&T industry organisations exhibit an enhanced ability to adapt and respond to the growing market demand for sustainability.

The results also illuminate a significant negative moderation effect of competitors' and customers' environmental orientation on the impact of green management practices on both business process performance and sustainable supply chain performance. This underscores the critical importance of considering the external context within which organisations operate. The actions and attitudes of other industry stakeholders, as evidenced by the environmental orientation of competitors and customers, wield influence over the efficacy of green supply chain practices (Gambardella et al., 2015). Consequently, organisations in the A&T industry must be cognisant of the environmental orientation prevailing among their counterparts and customer base to implement green supply chain practices and enhance both business process performance and sustainability performance.

The theoretical implications drawn from the hypothesis testing results in the A&T industry contribute valuable insights to the natural resource-based view, dynamic capabilities theory, and the significance of acknowledging the external context. These findings offer guidance for organisations in the industry aiming to refine strategies and practices, leveraging green supply chain practices to enhance business process performance and sustainability performance.

4.2. Managerial implications

The results of the hypothesis testing offer valuable insights for organisations aspiring to enhance their sustainable supply chain performance. The revelation that lean supply chain practices do not significantly impact business process performance implies that A&T industry organisations need to maintain efficiency to embrace sustainable practices. This resonates with the notion that sustainability and efficiency are not inherently contradictory; organisations can concurrently pursue both objectives (Gao et al., 2018). Furthermore, the correlation between enhanced business process performance and increased sustainability underscores the pivotal role of internal processes and operations in pursuing sustainability. To achieve efficiency and sustainability goals simultaneously, A&T industry organisations should prioritise optimising their business processes and operations (Lin & Chen, 2020).

The positive impact of Green Supply Chain Practices on business process performance in Jordan's

A&T industry suggests that companies should contemplate integrating green supply chain practices to enhance their business processes. Additionally, the finding that business process performance positively mediates the impact of green supply chain practices on sustainable supply chain performance underscores the importance of focusing on improving business process performance to elevate sustainability performance.

Conversely, the results did not substantiate the hypothesis that lean supply chain practices significantly impact business process performance in Jordan's A&T. This implies that companies can adopt lean supply chain practices without detrimentally affecting their business process performance. However, it is crucial to note that the results did not support the hypothesis that business process performance mediates the impact of lean supply practices on sustainable supply chain performance. Consequently, the influence of lean supply chain practices on sustainability performance remains unclear, necessitating further investigation.

Finally, the results indicate that the environmental orientation of competitors and customers can negatively moderate the impact of green management practices on business process performance and sustainable supply chain performance. This underscores the importance for companies to consider the environmental attitudes of their competitors and customers when implementing green supply chain practices. By doing so, organisations can maximise the positive effects of green supply chain practices on both business process performance and sustainability performance. This emphasises the need for a nuanced approach that acknowledges and aligns with the environmental perspectives of stakeholders in the industry.

Conclusions, limitations, and future directions

The imperative role of lean supply chain practices and green supply chain practices in shaping business process performance and sustainable supply chain performance, spanning economic, social, and environmental dimensions, underscores their indispensable relevance in the modern business landscape. In the fiercely competitive environment, the strategic imperative of minimising natural resource utilisation and mitigating societal and environmental impact stands as a linchpin for attaining a sustainable advantage over the long term. Companies navigating this terrain must perceive responding to environmental pressures as a strategic goal that is pivotal for enhancing business operations and realising sustainability in their supply chains.

This study augments the comprehension of the intricate mechanisms inherent in lean supply chain practices and green supply chain practices, elucidating the pivotal role played by the environmental orientation of competitors and customers in effecting transformative changes in business process performance within the unique context of a developing Middle Eastern nation like Jordan. Consequently, this research not only contributes valuable insights to the existing body of knowledge on supply chain practices but also furnishes compelling evidence underscoring the critical importance of the environmental orientation of competitors and customers in shaping the interplay between green supply chain practices, business process performance, and sustainable performance within A&T supply chains.

In consonance with the resource-based theory, which advocates for exploring contingent effects, this study highlighted the imperative of strategic planning and extensive design to facilitate the adoption of environmentally friendly products. This necessitates radical transformations in supply processes, procurement, storage, and material handling, though the short-term pressures may potentially impede process performance (Ferreira & Silva, 2022).

The resource-based view is that sustained high-performance levels necessitate the comprehensive integration of all supply chain members over the long term. This study, while focusing on the Jordanian industrial sector, opens avenues for future exploration across diverse sectors such as tourism and services. Prospective research endeavours may benefit from delving into causal relationships through longitudinal studies spanning extended time frames, offering insights with enhanced generalisability. Comparative studies leveraging data from various global markets can unveil nuanced similarities and differences, attuning findings to the unique dynamics of different contexts. Furthermore, future research may explore additional mediator variables influencing sustainable performance, including supply chain practices, total quality, dynamic capabilities, and information systems. Simultaneously, examining other moderation variables, such as the environmental orientation of suppliers and government, can enrich the research landscape by providing more holistic insights into the complex dynamics of sustainable performance within supply chains.

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Appendix A. Measurement scale items

Lean supply chain practices	
LP1	Our company adheres to the production schedule to generate the correct amount of output. (Dropped)
LP2	Our company follows an inventory control system that eliminates obsolete materials or products. (Dropped)
LP3	The company adopts process optimisation at the beginning of the inventory process to reduce its levels to a minimum. (Dropped)
LP4	The company follows the selection of optimal locations to reduce the need for packaging.
LP5	The company uses reusable packaging.
LP6	We recycle internally to reduce transportation. (Dropped)
LP7	We are pooling waste transport to reduce environmental impact per ton of waste. (Dropped)
LP8	We control essential parameters (setting mode, control card, etc.) to reduce defects.
LP9	Scraps are re-integrated into the process as raw material.
LP10	We follow process control to optimise material efficiency.
LP11	We follow strict rules and limit the material used to the right amount.
LP12	We reduce work-in-progress inventory to prevent damage to the material/product
Green supply chain practices	
GP1	We work with our major suppliers to incorporate environmental issues into our product design process (e.g., reduce consumption of material/energy; increase the use of environmentally friendly materials).
GP2	We work with our partners to incorporate environmental issues into our manufacturing process (e.g., reducing consumption of material/energy; and increasing the use of environmentally friendly materials).
GP3	We work with our partners to incorporate environmental issues into our delivery process (e.g., reduce consumption of material/energy; use recyclable packages).
GP4	We work with our partners to establish a recycling process for used and defective products.
GP5	We work with our partners to better manage the disposal of industrial wastes (wastewater, gas, and residue).
Business process performance, please indicate the relative impact of lean, green, and SC management practices on each of the following business process performance indicators.	
BPP1	Engineering (e.g., design complexity, R&D cost, unit cost of the product, engineering design change cost).
BPP2	Manufacturing (e.g., quality control, manufacturing process cost, manufacturing complexity, material cost, manufacturing lead time, process technology investment cost.
BPP3	Procurement (e.g., purchasing costs, order processing, purchased component variety).
BPP4	Logistics (e.g., work-in-process and finished goods inventory, inventory cost, purchased component inventory, transportation cost).
BPP5	Sales (e.g., demand forecasting uncertainty). (Dropped)
BPP6	Customer satisfaction.
BPP7	Sales/market share.
BPP8	Competitive advantage.
Sustainable supply chain performance, please indicate the relative impact of lean, green, and SC management practices on each of the following:	
SSCP1	We are reducing environment, SC, and responsiveness costs. (Dropped)
SSCP2	Improve customer satisfaction.
SSCP3	Saving time.
SSCP4	Improve service level.

SSCP5	Improve the responsiveness. (Dropped)
SSCP6	Improve organisation's agility.
SSCP7	Supporting customer and supplier collaboration. (Dropped)
SSCP8	Improve overall firm performance. (Dropped)
Competitors' environmental orientation	
CEO1	Our competitors have appropriate environmental certificates.
CEO2	Our competitors emphasise green values in their marketing activities.
CEO3	Our competitors make significant efforts to use environmentally friendly technologies.
CEO4	Environmental issues are very relevant for our competitors.
Customers' environmental orientation	
CuEO1	Environmental issues are very relevant for our customers.
CuEO2	Our customers have a strong preference for environmentally friendly products.
CuEO3	Our customers would be willing to pay more for environmentally friendly products.
CuEO4	Environmentally friendly offers positively influence our customers' product choices.

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Optimising picking operations in distribution centres: a simulation and algorithm-based approach for travel distance reduction

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ABSTRACT
This study examines the pivotal role of the logistics sector in corporations, particularly those with diverse product portfolios. It focuses on the time-intensive "picking" process, driven by various products and material handling requirements for order fulfilment. The research presents a methodology that combines distribution centre modelling for simulation with an optimisation algorithm to enhance operational efficiency. The goal is to determine an optimal route for product retrieval, minimising employee travel distances, using the simulated annealing algorithm. The results showcase a significant 7 % reduction in employee travel distance during collection. This research is relevant to academia and practical applications as it presents an opportunity to reduce operational costs in distribution centres, enhance the efficiency of picking operations, and improve the competitiveness of companies. Furthermore, it contributes to operations research by addressing a complex problem with significant practical implications using a rather unused method to solve this problem of picking operations. The approach is empirically applied in a prominent Brazilian beverage company. This methodology proves valuable for optimising logistics operations in various industrial contexts, highlighting its practical applicability.

KEY WORDS
logistics, picking, optimisation, simulated annealing, discrete simulation, digital manufacturing, distribution centre, logistics centre

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Introduction

Optimising picking operations in distribution centres is a highly relevant topic within logistics and operations management, given that the costs associated with this process can account for over half of the total operational costs (de Koster et al., 2007; Richards, 2018). In the broader context of the logistics and supply chain management literature, enhancing the efficiency of picking operations has been a constant concern. In this regard, strategies such as layout reconfiguration, automation technologies, and the

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analysis of item-picking sequences have been subject to investigation. However, as proposed in this study, restructuring the picking list for operators represents a valuable contribution to addressing the persistent challenges related to information updating in distribution systems, an issue often overlooked in academic literature and business practice.

The academic literature encompasses many studies that examine optimising logistics operations (Hsieh & Tsai, 2006; Van Gils et al., 2018). Nevertheless, a conspicuous research gap exists concerning the specific inquiry into the relationship between the picking list generated by the Warehouse Management System (WMS) and the physical layout of warehouses in distribution centres, particularly in the Brazilian context. This lacuna in research assumes pronounced significance in light of the potential consequences, given that a misalignment between these components can lead to superfluous expenditures and operational inefficiencies, a matter of paramount gravity in an industry where costs associated with operator movement and handling may eclipse 50 % of the total expenditure (De Koster et al., 2007; Richards, 2018).

More thorough research and analysis are needed to reduce picking time within distribution centre operations and address various challenges. These encompass operational inefficiency, resource profligacy, delivery delays, impediments to system updates, and a diminished competitive edge within the market. These repercussions translate into heightened costs, compromised operational efficacy, and customer discontent, underscoring the need for a scholarly and systematic approach to investigate and deploy optimisation strategies.

In summary, this study addresses the following research query: To what extent does utilising an optimisation strategy based on simulation and algorithms for finding shorter routes impact the reduction of travel distances for workers in the context of picking operations within distribution centres?

The primary aim of this study is to investigate the extent to which the implementation of an optimisation strategy grounded in simulation and algorithmic route selection influences the reduction of travel distances for workers engaged in picking operations within distribution centres. At this inquiry stage, the "central phenomenon" is broadly characterised as optimising picking routes in distribution centres.

This study will employ data collection, discrete event simulation modelling, and the simulated annealing algorithm to optimise picking operations in distribution centres, assessing the impact of the optimisation strategy on efficiency.

This research is relevant to both academia and practical applications as it presents an opportunity to reduce operational costs in distribution centres, enhance the efficiency of picking operations, and improve the competitiveness of companies. Furthermore, it contributes to operations research by addressing a complex problem with significant practical implications.

The second section of this paper will review relevant literature on the topic under examination. The third section will detail the methodology employed in this research. Results obtained from this methodology will be presented in the fourth section. Conclusions and anticipated contributions of this investigation will be discussed in the fifth and final section of the paper.

1. Literature review

This section delves into the following pivotal academic domains: (1) picking sector in logistics, (2) collection routing policies in warehousing environments, (3) optimisation in "picker-to-part" warehousing environments, (4) meta-heuristic approaches, (5) simulated annealing, and (6) simulation for discrete event modelling.

1.1. Picking sector in logistics

In logistics, warehouses play a central role in facilitating efficient customer service. Many companies have evolved their perception of warehouses from mere storage facilities to integral components contributing to customer satisfaction. Among various warehouse operations, the picking sector is particularly crucial for maintaining operational efficiency and improving customer service. The picking process involves selecting and segregating products into pallets based on customer orders for subsequent shipment. This process, defined as order picking, fulfils customer requests and can encompass a range of clients, including independent customers, organisations, or automated systems.

Kulak, Sahin and Taner (2012) categorise the picking process into two primary methods:

- Picker-to-Part: In this manual process, an operator is responsible for physically collecting items based on customer orders and navigating the warehouse to locate the specified items.

- Part-to-Picker: This automated process involves delivering items to the operator, eliminating the need for manual item retrieval.

Several factors influence productivity in the manual picking model, including warehouse layout, travel distances, delays during item collection, equipment preparation, information dissemination for subsequent retrievals, and the search for specific items. However, the most critical factor affecting efficiency is the physical movement of the operator during item retrieval. The choice of the operator's route significantly impacts the time and effectiveness of the process (Lu et al., 2016).

Determining the optimal collection route for a specific set of locations involves establishing an efficient sequence for collecting items. This sequence aims to minimise the distance travelled, optimise routes, streamline processes, and ultimately increase the product dispatch rate.

Among the various factors that can increase item collection times, the distance travelled by workers is predominant and can account for over 50 % of the collection time. Since travel time does not add value to the product and generates additional costs, reducing travel time is crucial for minimising operational expenses in picker-to-part systems (Lu et al., 2016). De Koster (2007) underscored the importance of reducing travel distance to decrease picking time and improve operational efficiency in warehouse operations.

The picking sector has received extensive attention from researchers, encompassing strategic and operational aspects. Diefenbach and Glock (2019) categorise warehouse problems into five areas: layout, product allocation, zone allocation, batch picking, and operator collection routes. This study focuses on optimising operator collection routes to reduce the distance travelled by operators.

1.2. Collection routing policies in warehousing environments

Collection routing policies represent a critical facet of warehouse operations, with their principal objective being the minimisation of the distance traversed by operators while retrieving customer order items. This strategic pursuit primarily aims to mitigate operator fatigue, curtailing task execution durations and thereby augmenting overall operational efficiency. Masaiek, Glock, and Grosse (2019) underscored the paramount importance of this subject matter. Notably, within the context of order-picking processes, where travel time accounts for more than 50 % of the total dedicated time, the scientific community has directed considerable attention towards the intricate nuances encompassing collection routing policies. Several academic compendia and bibliographic surveys, including seminal works such as

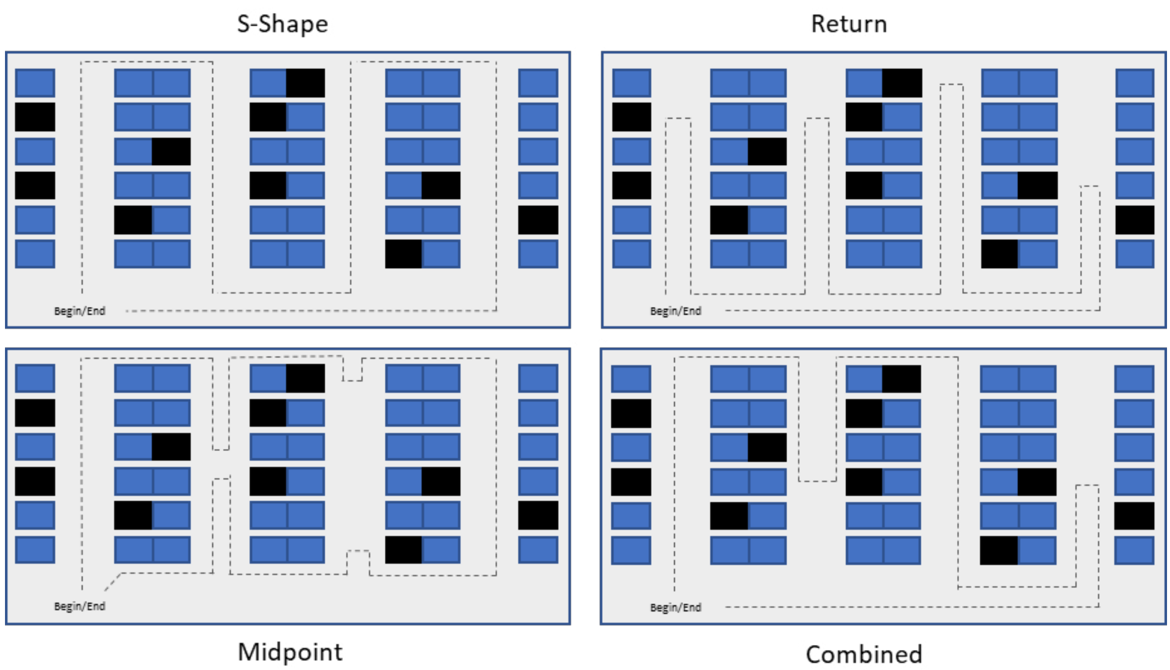

Fig. 1. Illustration of methodological approaches to picking areas

those authored by Grosse, Glock and Neumann (2017) and van Gils et al. (2018), have contributed to the comprehensive exploration of this domain.

Within the ambit of collection routing policies, a taxonomy of methodological approaches has emerged, each distinguished by unique nomenclature and specific operational mechanisms. Some of these methodologies, i.e., s-shape, return, midpoint, and combined, are outlined by Sancakli (2022) and illustrated in Fig. 1.

The methods illustrated in Fig. 1 were described by van Gils et al. (2018). The s-shape method requires the operator to visit every corridor, as long as at least one item needs to be collected while entering the next corridor on the same side they left the previous one. The return method indicates that the operator should always enter and leave the corridor by the same side, as long as the corridor has any product to be picked.

The midpoint method requires the operator to collect at least one item and go halfway through it. If a corridor has items on both sides, the operator should first collect the ones on one side, and later, when completing the route, they should enter the other end of the corridor to collect the items on the other side. Lastly, the combined method indicates that the operator can go through an entire corridor, leave it, go to the next, walk halfway through that corridor and leave it by the same end they entered and so on, mixing the s-shape and midpoint methods.

Heuristics, as mentioned above, are widely applied to solve operator routing problems due to advantages in computational efficiency and easy implementation (Cortés et al., 2017).

1.3. Optimisation in "picker-to-part" warehousing environments

Several facets warrant scholarly inquiry in warehouses utilising the "picker-to-part" operational paradigm. As posited by Li, Huang and Dai (2017), four distinct avenues of investigation emerge: the optimisation of warehouse layout, product allocation within storage positions, batch-picking strategies, and route optimisation for operatives engaged in item retrieval tasks.

The notion of reevaluating the trajectories undertaken by operators during item collection has garnered substantive scholarly attention, frequently drawing analogies with the renowned Traveling Salesman Problem (TSP) (Li, Huang & Dai, 2017). Some scholars categorise this endeavour within multi-aisle warehousing configurations as a specific instance of the Steiner Traveling Salesman Problem (STSP) (Kulak, Sahin & Taner, 2012).

Notably, it is incumbent to acknowledge that determining the picking operator's route represents an NP-Hard (Non-deterministic Polynomial time) computational conundrum. Given this inherent complexity, problem resolution is typically pursued by adopting heuristics or optimisation methodologies (van Gils et al., 2018; Li, Huang & Dai, 2017). Heuristic approaches are conventionally enlisted, aware that they do not guarantee optimality. However, they offer a viable pathway to convergence towards a generally satisfactory solution, provided that the problem has been adequately comprehended and modelled (Diefenbach & Glock, 2019). Notably, applying optimisation methods persists in pursuing an optimal outcome, notwithstanding their computational demands and the intricacies involved.

As expounded by Masae, Glock and Grosse (2019), the extant literature has proposed three distinct categories of algorithms to address this challenge:

- Exact algorithms are characterised by their ability to invariably discern an optimal solution, as the Traveling Salesman Problem exemplifies.
- Heuristic algorithms are problem-specific and tailored to produce reasonably proficient solutions across most instances, exemplified by the "S-shape" and "Midpoint" methodologies.
- Meta-heuristic algorithms transcend problem specificity and furnish high-level guidelines and strategies to offer approximate solutions, exemplified by the bee colony and ant colony algorithms.

1.4. Meta-heuristic approaches

Another avenue for investigating how optimal operator routes are determined lies in deploying meta-heuristic techniques, constituting a set of guiding principles for crafting optimisation algorithms tailored to operator routing challenges (Kulak, Sahin & Taner, 2012). As highlighted by Cortés et al. (2017), prior research has explored the application of meta-heuristic algorithms, including genetic algorithms, ant colony optimisation, and particle swarm optimisation, to address operator routing problems.

Pinedo (2018) augments this discourse by enumerating prevalent meta-heuristic algorithms, encompassing simulated annealing, tabu search, genetic algorithm, ant colony optimisation, beehive, and others. These algorithms are categorised as local search algorithms and further — into improvement and constructive subcategories. Improvement-type algorithms commence their procedural trajectory with a randomly generated solution and iteratively seek enhanced outcomes by manipulating preselected variables at the outset of the process. Notably, local search methodologies do not guarantee optimality but consistently strive to improve the incumbent solution. Determining termination criteria is incumbent upon the programmer and contingent upon the improvement level achieved through iterative cycles.

Ardjmand, Sanei Bajgiran and Youssef (2019) offered insights into the work of Matusiak et al. (2014), wherein simulated annealing was harnessed to investigate batch formation under precedence constraints and operator routing. Their approach encompassed two sub-algorithms: an a-star algorithm for routing solutions and simulated annealing for batch-related challenges. Their findings demonstrated less than 1.2 % errors compared to optimal solutions involving more than three orders.

Furthermore, Ardjmand, Sanei Bajgiran and Youssef (2019) expound upon the research by Chen et al. (2015), who formulated a mixed-integer nonlinear programming model to address batch, sequencing, and operator routing challenges, all geared towards minimising order execution times. Their innovative approach amalgamated the capabilities of genetic algorithms and ant colony optimisation to resolve these intricate logistical issues. Similarly, Cheng et al. (2015) introduced a hybrid methodology comprising particle swarm optimisation and ant colony optimisation to tackle batch-related challenges and operator routing complexities.

However, it is noteworthy that most extant research endeavours and studies confine their scope to predefined warehouse layouts. While such constraints do not necessarily undermine the applicability of the aforementioned meta-heuristic algorithms, they can curtail the universality of their deployment. It is pertinent to underscore that several studies scrutinising picking operations also delve into item allocation intricacies and the architectural configuration of the picking area. In light of these limitations, this present work endeavours to conceptualise a solution framework agnostic to the peculiarities of warehouse layouts.

1.5. Simulated annealing

Simulated annealing, initially introduced by Kirkpatrick et al. (1983) and Cerny (1985), originated from the adaptation of an algorithm developed by Metropolis et al. (1953) for modelling atomic arrangements in solids aimed at achieving the lowest energy state, a process analogous to cooling. Kirkpatrick et al. and Cerny recognised its potential application in optimisation problems, establishing analogies between the physical system and combinatorial optimisation:

Optimisation solutions correspond to physical states.

- The cost of an optimisation solution is analogous to the energy of a physical state.
- The selection of a neighbouring solution in optimisation mimics the perturbation of a physical state.
- The global optimum in optimisation aligns with the ground state in the physical system.
- Local optima in optimisation resemble rapid cooling phenomena in the physical system.

Simulated annealing operates as a "refinement heuristic" algorithm, initiating with an arbitrary solution and aiming to improve it through variable manipulation and local search. Importantly, it does not guarantee optimality. Its primary objective is to find a nearby solution superior to the current one. Each iteration explores potential solutions in the vicinity, accepting or rejecting them based on intrinsic criteria. This iterative process is designed to escape local optima and converge toward global optima (Pinedo, 2018).

Grounded in statistical mechanics, simulated annealing commences with a random solution. During each iteration, it explores neighbouring solutions. If a neighbouring solution is superior in the objective function, it becomes the new current solution; otherwise, its acceptance depends on the probability of accepting "worse results". The temperature parameter determines this probability. As simulated annealing progresses, the temperature gradually decreases, reducing the acceptance of "worse results". Cooling strategies can vary, with two common approaches being fixed-rate cooling and percentage-based cooling until a low temperature is reached. It is worth noting that simulated annealing is highly sensitive to this temperature parameter, necessitating careful tuning to ensure effective convergence (Ardjmand, Sanei Bajgiran, & Youssef, 2019).

Simulated annealing is employed as an optimisation tool to locate global optima within extensive search spaces by simulating the cooling process until a stable state is reached (Fayyaz et al., 2018). Fig. 2 illustrates the expected behaviour when employing

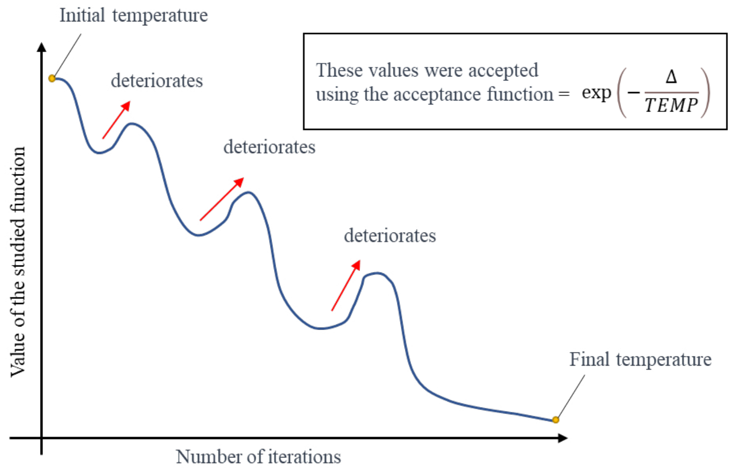

Fig. 2. Expected behaviour when accepting deteriorations

this algorithm. The method initiates with a high temperature to facilitate the escape from local minima and accepts "worse results". As the temperature decreases, the acceptance of "worse results" diminishes, allowing the algorithm to avoid getting trapped in local minima given sufficient iterations or time (Fayyaz et al., 2018).

The likelihood of accepting deteriorating solutions is determined by the acceptance function ($g\ (\delta, T)$), typically represented as exp(−δ/T), where δ represents the difference between solutions, and T is the temperature parameter. When $\delta = f(j) - f(i)$ is less than zero, solution j is accepted as the new current solution. Conversely, it is only accepted if the acceptance function exceeds a random value ($g\ (\delta, T) > random\ (0,1)$).

Simulated annealing begins with a relatively high temperature to prevent premature convergence to local minima. The temperature is gradually reduced, and multiple attempts are made to improve solutions near the current solution for each temperature value. The algorithm terminates when a predefined stopping criterion is met, which can be related to the final temperature value. However, depending on the cooling rate, it may take considerable time and computational resources to reach this point. It is also common to set an iteration limit for each temperature. Once this limit is reached, the algorithm accepts the current function value, regardless of whether it has completed the desired processing and cooling of the function (Sibalija, 2018). A flowchart showing its processes is depicted in Fig. 3.

1.6. Simulation for discrete event modelling

Simulation for discrete event modelling is a widely employed technique for modelling systems that evolve in discrete time instants, contingent upon the occurrence of specific events. This approach enables the analysis of "what if" scenarios, facilitating the evaluation of how alterations in one or more parameters influence the behaviour of a given system. To this end, the simulation modeller must possess proficient modelling, analysis, and decision-making skills to derive meaningful results. It is worth emphasising that simulation is a tool for conducting tests in operational scenarios but does not guarantee optimal outcomes. Nevertheless, when applied judiciously, it can yield substantial results.

Therefore, while discrete event simulation aims to represent real systems as closely as possible, it provides the modeller with the ability to better understand the studied system, making it possible to identify excess capacity, constraints, bottlenecks, and uneven utilisation, which can be provided with a solution after testing on different scenarios (Forbus & Berleant, 2022).

According to Pegden, Shannon and Sadowsky (1990), simulation can be used to test hypotheses to confirm how and why certain events occur. Consequently, it allows for the measurement of the performance of a real system concerning different operational situations (Law, 2007). Thus, computational simulation can prevent misguided decisions that may jeopardise a company's operation or result

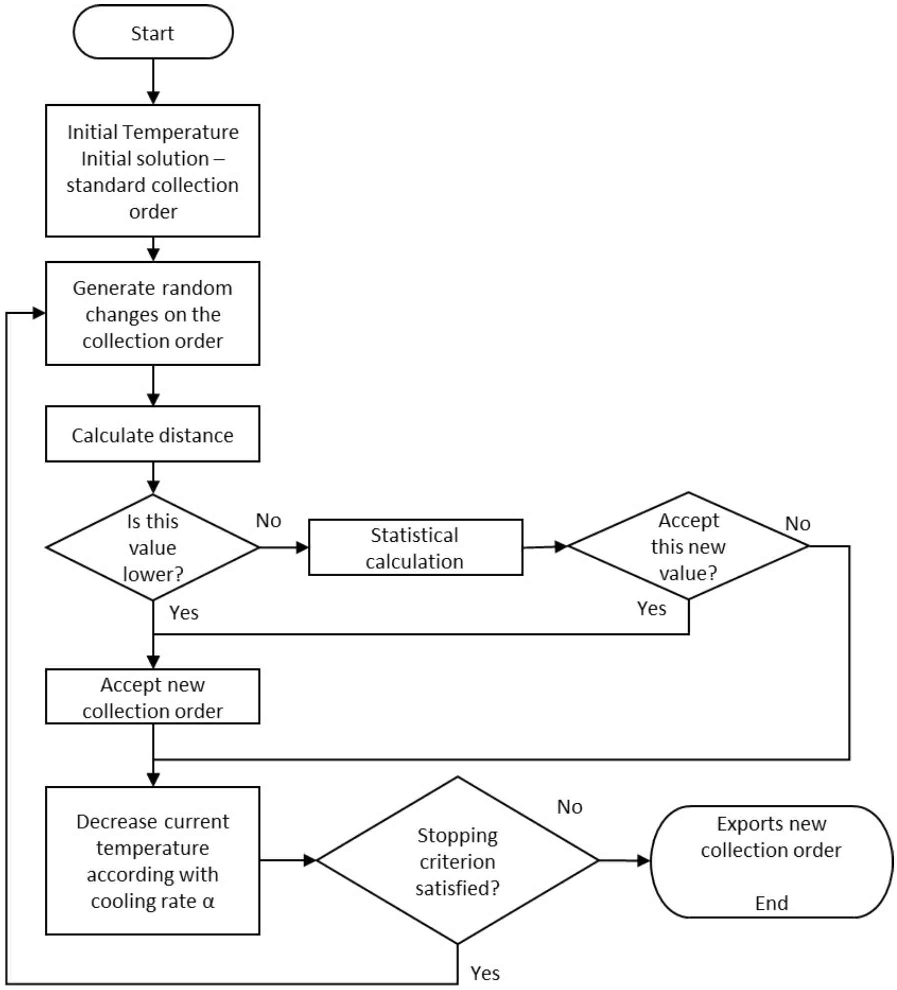

Fig. 3. Flowchart of simulated annealing

in inappropriate investments (Krajewski & Ritzman, 2001).

According to Law & Kelton (2000), simulation offers the following benefits:

- Development of adaptable models reflecting reality, testing various scenarios and operational possibilities of a system without resource commitment.
- Ability to simulate complex systems (possessing stochastic elements) inadequately described by deterministic mathematical models.
- Evaluation of the distribution of available resources, allocating them appropriately to the process and ensuring high production levels.
- Better control over experimental conditions compared to practical implementation in the real system.
- Analysis of long periods of time of an option within a reduced simulation time.
- Identification of existing bottlenecks in the system and studies related to process optimisation.

Thus, simulation serves as a powerful means to support decision-making, enabling potentially good solutions to real system problems. However, to obtain applicable results that reliably represent the reality of a system, it is necessary to apply well-defined modelling and simulation techniques.

In parallel with the work conducted by Ardjmand, Sanei Bajgiran and Youssef (2019), this study also seeks the utilisation of tools that enable the efficient evaluation of operator routes within a specific layout, leveraging simulation models to obtain critical parameters aimed at optimising picking routes.

As elucidated by Dijkstra and Roodbergen (2017), two primary methods exist for assessing the distance travelled in collection routes. The first entails the creation of a simulation model, while the second involves the development of formulas grounded in the statistical properties of adopted route models. The authors employed both methods to assess the allocation of storage locations in a warehouse to minimise the distance travelled and found substantial agreement between the results obtained through the simulation model and the developed mathematical methods.

In a context akin to the present study, Quader and Castillo-Villar (2018) underscored the significance of decision management as a pivotal factor in the pursuit of efficiency enhancement and cost reduction in warehouse operations. These researchers proposed a simulation model that tests different route and SKU allocation heuristics to maximise operator utilisation or reduce order cycle times. This model allowed for evaluating how the system would dynamically perform in a picking zone with multiple aisles.

2. Research methods

This study proposes integrating a discrete event simulation model with applying the optimisation algorithm known as simulated annealing. The outlined approach necessitates acquiring and using information about the picking area within a Distribution Center. This entails constructing the simulation model based on the collected data, virtually generating data that may be challenging to obtain physically and applying the simulated annealing algorithm (Fig. 4) to determine the optimised collection route to maximise operational efficiency.

The concluding phase of the methodology addresses the validation of the distance covered by operators while following the optimised route, comparing it with the route suggested by the optimisation algorithm. This validation is conducted once again through the discrete event simulation model.

2.1. Simulation model

The model employed for this study has been crafted using Siemens' Plant Simulation software. The primary aim of this model is to represent the warehouse system and its operational dynamics. However, it is noteworthy that the discrete event aspect, which introduces stochastic elements through statistical distributions, has been deliberately excluded. The model serves two principal functions.

The initial function pertains to creating a "from-to" table, elucidating the distances between all positions within the warehouse (Fig. 5). It is imperative to underline the critical significance of this dataset for the subsequent execution of the route optimisation algorithm. In the authentic operational milieu, acquiring these values is a formidable undertaking, primarily due to the time-intensive nature of data procurement and the inherent impracticality of allocating human resources to undertake this task within a sector of the enterprise characterised by nearly continuous operations throughout the day.

The efficacious execution of this task requires utilising the physical layout of the company premises, complete with scales, corridors, and actual spatial configurations, which is indispensable as a foundation for constructing a model. This model is predi-

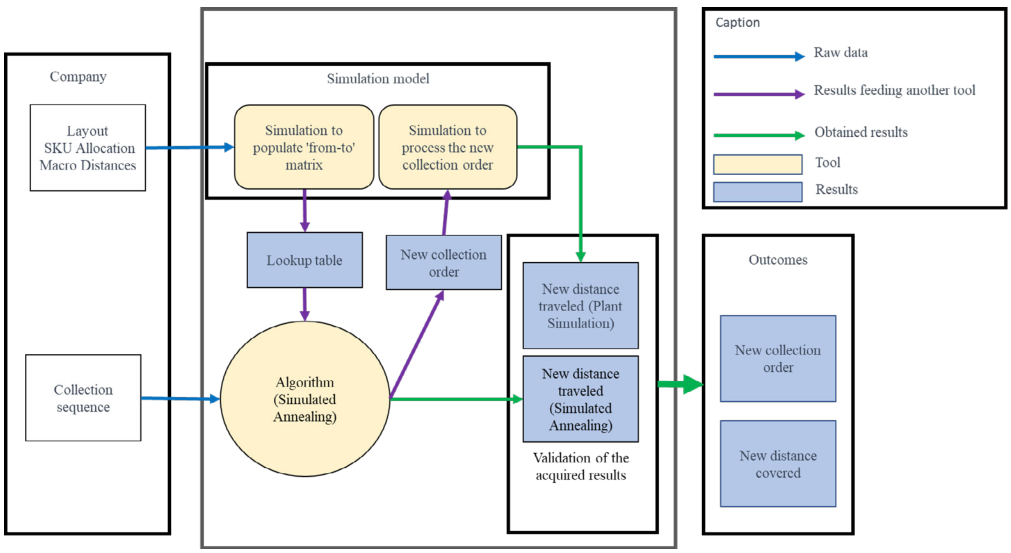

Fig. 4. Flow of the proposed methodology

cated on this empirical data and incorporates the locations of collection points corresponding to each pallet position. Once the model has been judiciously fashioned, an operative command may be executed, instructing an operator to traverse from a designated place A to all other positions, meticulously recording the inter-position distances within a "from-to" table. This meticulously compiled dataset is earmarked for prospective utilisation by the route optimisation algorithm. Fig. 6 furnishes a brief yet illuminating exemplar elucidating the procedural intricacies entailed. It visually encapsulates the operator's movements during data acquisition, with recorded data being meticulously chronicled within a spreadsheet.

Fig. 7 embodies a segment of the meticulously populated spreadsheet engendered through the agency of the simulation model. Herein, the first column is dedicated to enumerating the terminology of all positions, while the initial row designates the terminus to which the operator's peregrination must be directed.

This repository may be seamlessly integrated into the route optimisation algorithm after consummating the function mentioned earlier and comprehensively filling the "from-to" table with distance data. This symbiotic amalgamation facilitates the retrieval of pertinent data necessary for the second function of the simulation model (Fig. 8). In this subsequent phase, supplementary elements are introduced into the model's operational purview in addition to the data employed so far. These include, among other things, the allocation of products within respective positions and the imposition of a novel order for collection, as proffered by the route optimisation algorithm. These augmentations empower the model to scrutinise and appraise the aggregate distance traversed by operators while effecting the fulfilment of all orders within the ambit of the study period. This invaluable metric substantiates the basis for a comparative analysis of both methodologies, thereby affording insight into the efficacy of the respective tools.

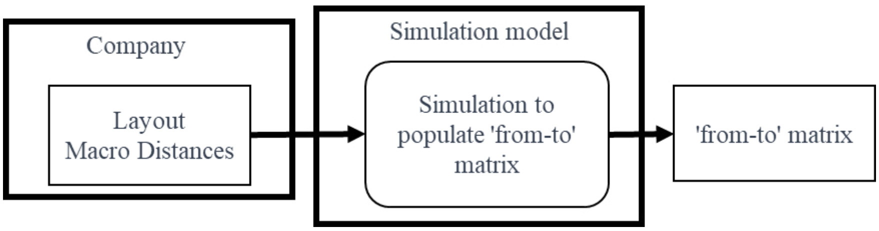

Fig. 5. Representation of the first function of the simulation model

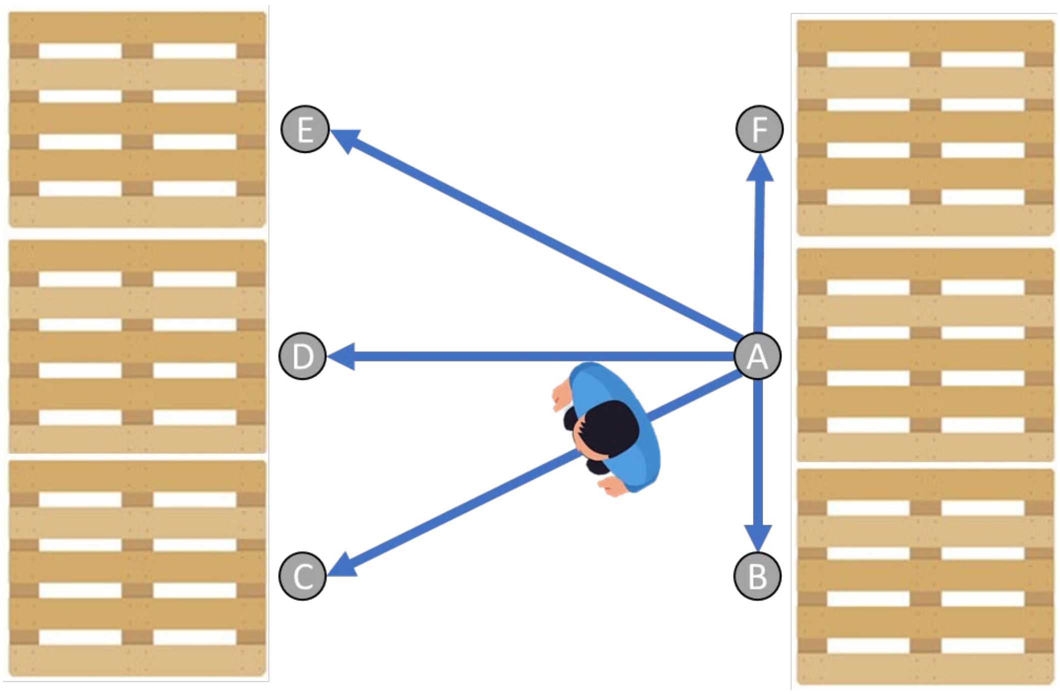

Fig. 6. Example of distance collection

	string 1	string 2	string 3	string 4	string 5
1		.CDD.Norte.OA001	.CDD.Norte.OA002	.CDD.Norte.OA003	.CDD.Norte.OA004
2	OA001	0	1.060546875	2.12109375	3.181640625
3	OA002	1.060546875	0	1.060546875	2.12109375
4	OA003	2.12109375	1.060546875	0	1.060546875
5	OA004	3.181640625	2.12109375	1.060546875	0
6	OA005	4.2421875	3.181640625	2.12109375	1.060546875
7	OA006	5.302734375	4.2421875	3.181640625	2.12109375
8	OA007	6.4638671875	5.4033203125	4.3427734375	3.2822265625
9	OA009	4.04271457628784	5.08155279817584	6.1278328864355	7.17830148960638
10	OA010	1.81452171434648	2.5190680972737	3.41298087508767	4.38185944284487
11	OA011	1.57759100310795	1.81452171434648	2.51906809725915	3.41298087508767

Fig. 7. Example of "from-to" table

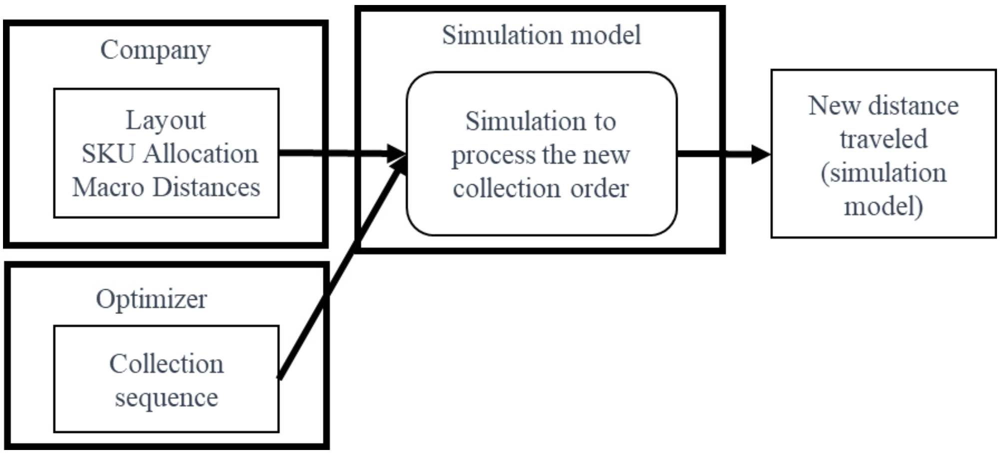

Fig. 8. Representation of the second function of the simulation model

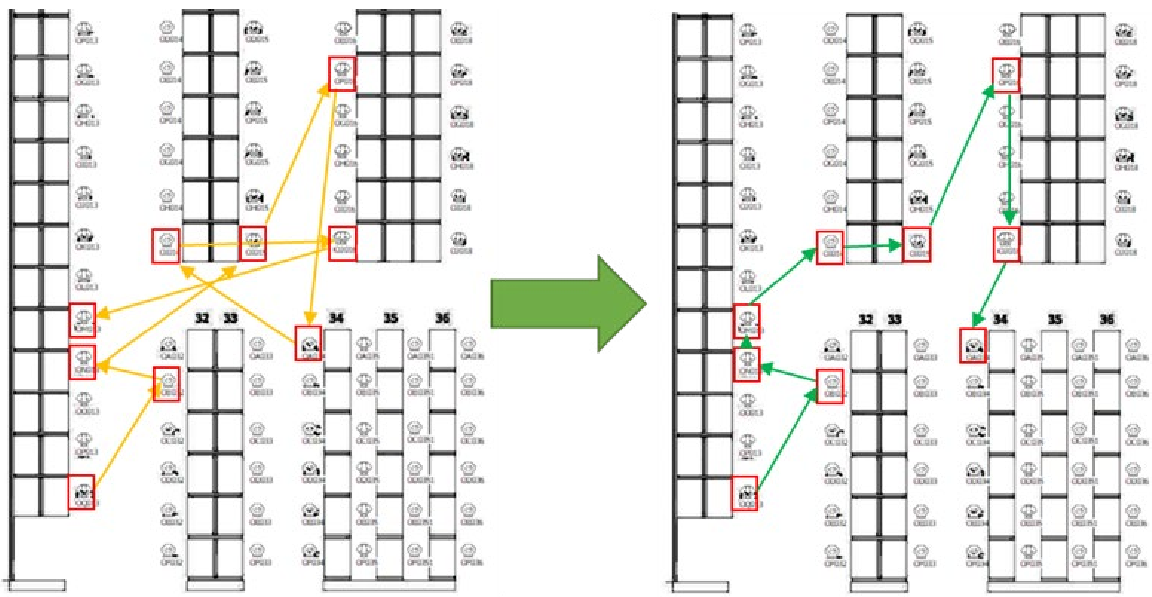

Fig. 9. Example of a reorganised collection route

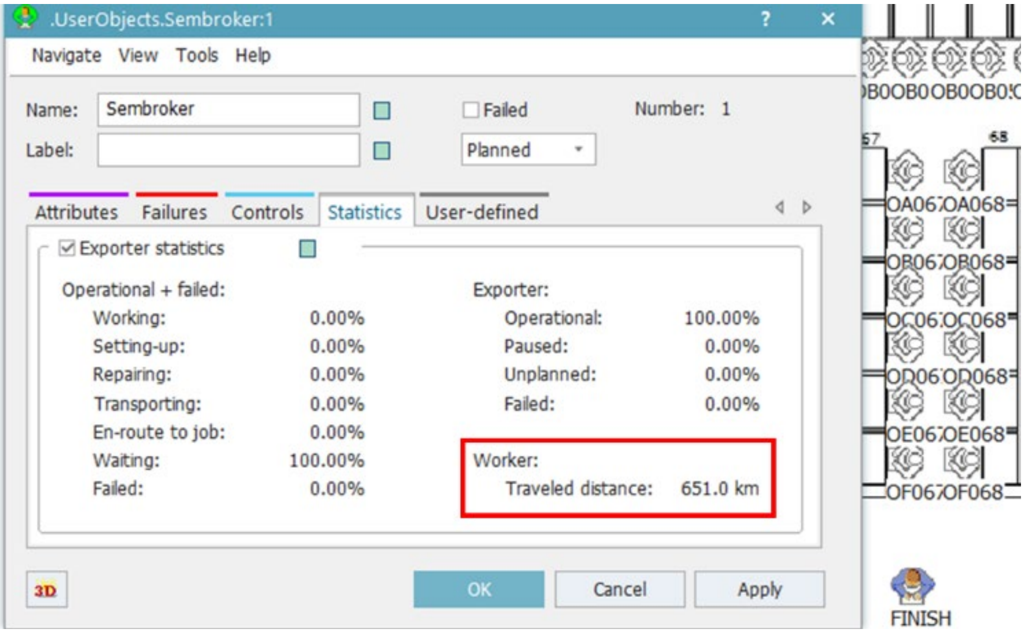

Fig. 10. Presentation of results

During this phase, the operative uses the newly prescribed collection route for gathering items. Notably, in certain instances, these routes may need to be more efficient, thereby accentuating the total distance covered by operators. However, such inefficiencies are rectified by applying the chosen optimisation methodology, simulated annealing (Fig. 9).

For both functions delineated above, the simulation model accords due consideration to the real-world dimensions of the warehouse.

Upon traversing all collection routes, the simulation model is primed to proffer a comprehensive exposition of the total distance covered (Fig. 10). Two distinct rounds of analysis are executed to facilitate a rigorous comparative evaluation. The initial round adheres to the original sequence of operations, whereas the subsequent round adopts the reordered sequence. The intent is to discern and evaluate operator dispositions to ascertain whether the new item collection sequence for orders exhibits superior efficiency.

2.2. Route study algorithm

The algorithm employed for route optimisation in this study has been founded upon the simulated annealing methodology, which was deliberately chosen due to its inherent capability to converge towards favourable outcomes efficiently. This method was selected for its agility, which renders it suitable for deployment in the routine operations of enterprises characterised by the picking process, and for its relatively straightforward implementation. Notably, alternative optimisation algorithms, including particle swarm and ant colony, were subjected to experimentation. However, the results could have been more attainable in one instance. At the same time, the feasibility of configuring the algorithm with the data and variables available for this study proved elusive.

The algorithm's initialisation phase encompasses the specification of control parameters pertinent to the simulated annealing method. These parameters contain the initial temperature, the final temperature, and the cooling rate. After parameter delineation, the algorithm necessitates inputting initial data elements. These comprise the extant collection sequence, the "from-to" distance matrix, and supplementary attributes germane to products associated with multiple pallet positions. Once these inputs are ascertained, the algorithm calculates the cumulative distance incurred by the initially proposed solution.

The subsequent phase embarks upon the operationalisation of the simulated annealing algorithm, a process contingent upon the current temperature surpassing the predefined final temperature threshold, serving as the algorithm's termination criterion. During this phase, permutations are systematically executed, substituting one item for another within the extant collection sequence. The objective is to evaluate prospective reductions in the total distance traversed by the assisting operators. Distance metrics are recalculated after each permutation, employing

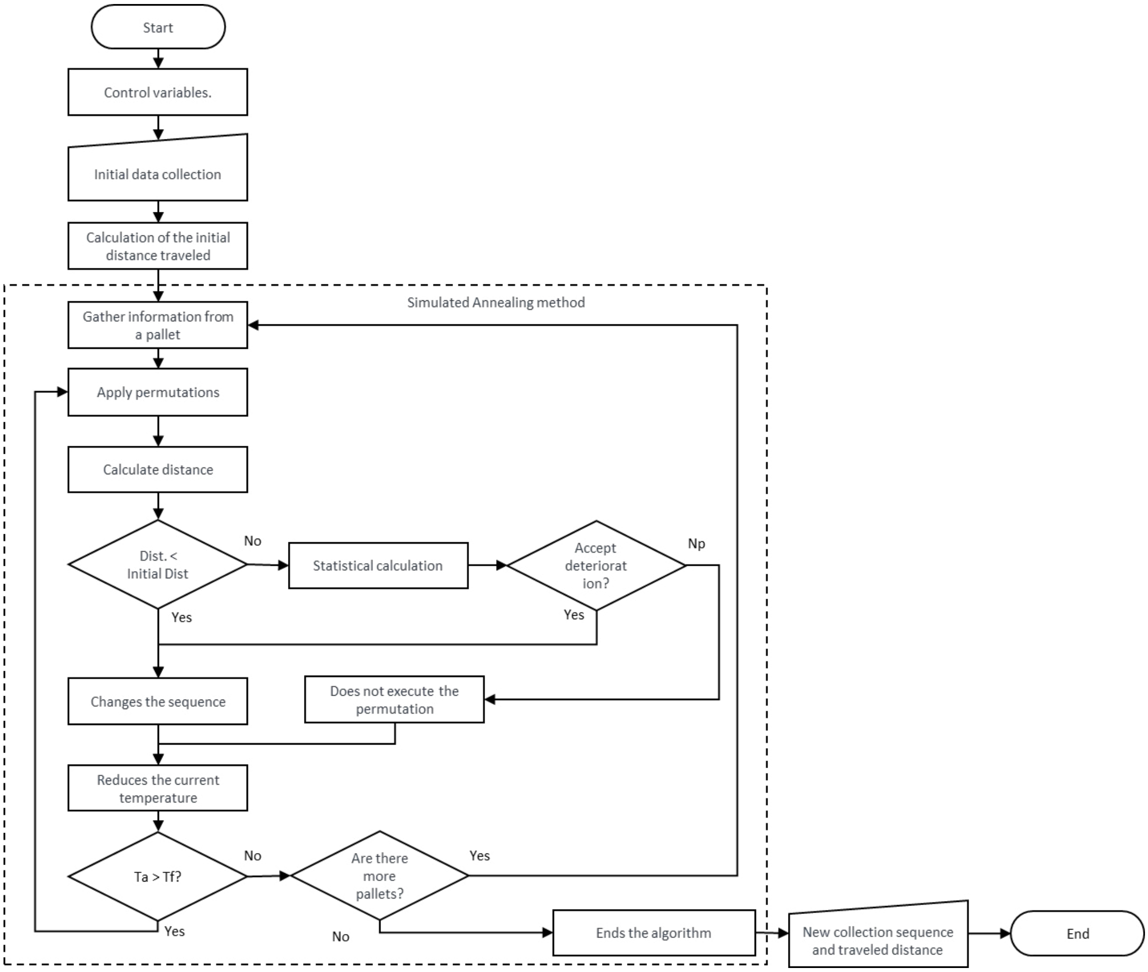

Fig. 11. Flowchart of the proposed algorithm's operation

the nearest neighbour rule as the heuristic measure. An alternative to the most immediate neighbour rule could have entailed deploying an exact method, the Traveling Salesman Problem algorithm. Other options include the heuristics (s-shape, return, mid-point, combined, and others), although they might not converge to an optimal result while needing little computational power to provide a solution. Furthermore, other meta-heuristics, such as tabu-search, genetic algorithm, and beehive, can be used to calculate and find a solution for this problem. This work used simulated annealing due to the difficulty of acquiring data from the actual picking zone, solving this by the "from-to" matrix acquired by the simulation model.

Nevertheless, this avenue should have been pursued, given the anticipated escalation in computational complexity. Consequently, computational expenses and processing timeframes could escalate to levels that preclude the practical application of this algorithm. This consideration is accentuated by selecting a compiled programming language, which tends to extend computational times. Importantly, it should be underscored that permutations are confined solely to items in the same pallet. This deliberate constraint safeguards against inadvertent allocations of products to orders for which they were not requisitioned.

Post-permutation distance calculations engender an assessment of disparities between the newly derived distance and the original benchmark. In cases where the recalculated space proves to be shorter than the original, the algorithm affects a substitution of the extant collection sequence with the revised variant. Embracing the core principles of simulated annealing, a statistical procedure presides over the determination of the acceptance or rejection of ostensibly suboptimal outcomes. This statistical regimen operates with the purpose of forestalling entrapment within local minima and facilitating the exploration of superior solutions. Consequently, even when the recalibrated distance exceeds the original metric, a consultation invokes a function adjudicating whether the revised value warrants acceptance as a valid response. This process promotes the formulation of a novel collection sequence.

After each iterative cycle, the algorithm orchestrates a systematic temperature reduction per the predefined cooling rate established at the inception of the algorithmic process. This modus operandi precipitates alterations within the item collection sequence encapsulated within the pertinent order. These permutations continue unabated until the temperature descends to a point below the stipulated final temperature or until the universe of potential swaps within the confines of the order or pallet becomes wholly exhausted. At this juncture, an evaluation is conducted to ascertain the existence of any residual unanalysed pallets. The procedural cycle iterates until no further pallets remain available for permutation. The outcome of this algorithmic endeavour furnishes a novel sequence for item collection, along with a precise calculation of the requisite distance for the execution of this collection itinerary.

Fig. 11 illustrates a comprehensive flowchart encapsulating the sequential operations executed by the proposed algorithm, meticulously aligning with the procedural description.

2.3. Integration of models

The fusion of the simulation model and the route optimisation algorithm through applying the simulated annealing methodology constitutes a crucial aspect of this research. This section outlines the procedural framework that governs this integration.

As depicted in Fig. 4, data flow within the proposed framework is structured as follows: the dataset provided by the organisation, encompassing the facility layout, inter-corridor distances, SKU allocation, and the existing collection sequence, serves as the external input for the route optimisation algorithm. The collection sequence forms the core of this algorithm, guiding simulated annealing-based reconfiguration. The remaining dataset elements are used in the simulation model. This model has a dual purpose. First, it constructs a "from-to" matrix, providing essential data for the route optimisation algorithm, which would be challenging to collect physically.

The route optimisation algorithm begins after receiving the necessary dataset (the "from-to" matrix, SKU positions, and collection order). It generates a new collection order and calculates the distance covered under this new sequence. The simulation model is then used to validate the results. The new collection order is inputted into the model to extract the distance covered. This allows for a comparison to assess whether the new collection sequence reduces the overall distance travelled by operators.

3. Research results

This section presents and discusses the results obtained through the methodology proposed in the previous chapter, which combines a simulation model and the simulated annealing algorithm. The simulation models were developed using Siemens's Plant Simulation software. The programming language used for the algorithm was Python. The choice of Python was based on prior familiarity with the language. The programming was implemented in Python version 3.8.4, adding the NumPy 1.19.0 library. Other libraries used were native to Python and did not require external additions; they were imported using standard Python commands. For instance, the "math" library contains complex mathematical functions, and the "threading" library allows for multithreading, a parallel computing technique that enhances the efficiency of tasks within the program.

3.1. Experimental design

Adopting a three-step approach necessitates consideration of distinct variables within each step, some of which may warrant more extensive analyses than others.

The experiment does not necessitate repetitive iterations in the initial step, involving the simulation model for data collection to construct the "from-to" matrix. This is attributed to the absence of factors capable of introducing variability. The model's function is straightforward, involving a systematic traversal of all positions without stochastic components to populate the requisite table for the subsequent phase.

Subsequently, applying the simulated annealing algorithm for route analysis introduces certain variables that can potentially enhance accuracy, albeit at the cost of heightened computational complexity and, concomitantly, increased computational time. In this experiment, the sole variable under scrutiny pertains to the cooling rate. Remarkably, the initial and final temperatures ($T_i = 1$ and $T_f = 0$) were main-

Tab. 1. Summary of simulated annealing results

Cooling Rate (C.R.)	Initial distance (km)	Reorganised distance (km)	Difference (km)	Difference (%)	Execution Time (h)
0.5	706.26	652.61	53.65	7.60%	0.7
0.9	706.26	649.13	57.13	8.09%	5.4
0.99	706.26	648.01	58.25	8.25%	46

Tab. 2. Results after execution in the simulation model

Cooling Rate (C.R.)	Initial distance (km)	Optimised distance (km)	Difference (km)	Difference (%)
0.5	705.68	655.05	50.63	7.17%
0.9	705.68	651.88	53.8	7.62%
0.99	705.68	651.01	54.67	7.75%

Tab. 3. Comparison between scenarios

Scenario	S.A. Distance (km)	Simulation Distance (km)	Difference (km)	Difference (%)
Initial	706.26	705.68	0.58	0.08%
C.R. = 0.5	652.61	655.05	2.44	0.37%
C.R. = 0.9	649.13	651.88	2.75	0.42%
C.R. = 0.99	648.01	651.01	3.00	0.46%

tained as constants throughout all executions. Three discrete cooling rates, empirically determined as 0.5, 0.9, and 0.99, were examined to ascertain the trade-off between computational runtime and the extent of achieved optimisation.

The inaugural algorithm run was executed with a cooling rate set at 0.5 to assess the feasibility of expedited convergence toward a solution. Given that this initial run successfully proposed a comprehensive reorganisation of all orders spanning a month of operational data within slightly over 48 minutes, it became evident that elevating the cooling rate was a plausible course of action. Subsequent experimentation with a cooling rate of 0.9 produced superior results but incurred a computational time expenditure of approximately five and a half hours. The culminating investigation entailed the application of a cooling rate of 0.99, the primary objective being to determine the degree of optimisation attainable, irrespective of computational time. This ultimate test endured for approx. 46 hours, yielding a further reduction of 0.2 % in the absolute distance traversed by workers in contrast to the preceding experiment.

The conclusive phase encompasses simulation activities to substantiate the outcomes derived from the newly prescribed collection order. In alignment with the previous steps, wherein variations were notably absent within the model designed for constructing the "from-to" matrix, the simulation results retained uniformity when comparing outcomes across the three separate testing iterations.

Initially, this methodology was applied to one of the units of a large beverage company, which provided data on pallet assembly, monthly orders, macro-layout distances, and product allocations. Table 1 summarises the results obtained from the route optimisation algorithm, showing the distance covered during the analysed period (one month), the difference between the initial and reorganised distances, and the execution time for different cooling rates.

For this studied warehouse, the simulated annealing algorithm resulted in a reduction of over 7.5 % in the total distance travelled by the operators. These values are now compared to the simulation model. Table 2 presents the results obtained after this execution, which indicate that using the sequence proposed with the lowest cooling rate would allow for a possible reduction of 7.17 % of the original distance, representing over 50 km of reduced distance travelled in a month.

Comparing the results obtained by both methods, it can be concluded that the application of the simulated annealing algorithm results in a reduction of the distance travelled. This reduction was validated by applying the suggested sequence in a simulation model, as there was no scenario with a difference greater than 0.5 %. The comparison between the results is shown in Table 3.

With low error rates when comparing the algorithm and the simulation model, along with results indicating a reduction in the total distance travelled, the simulated annealing algorithm is a viable option for application in this problem.

4. Analysis of the results

Three aspects warrant a discussion concerning the obtained results: execution time, the derived value and its significance, and the distinctiveness of individual warehouses.

4.1. Execution time

Significant variance in execution times occurred when modifying the cooling rate. The tool executed processes expeditiously for the lowest value (0.5), rendering results within an hour and employing a value of 0.9, which increased execution duration substantially, reaching around 5.5 hours. This remains acceptable given the algorithm's stochastic nature and tolerance for outcomes that marginally degrade performance. In contrast, the highest value (0.99) resulted in exponential runtime expansion, surpassing 45 hours. This extended duration resulted in a more significant number of iterations; however, it could have yielded more substantially improved results, with only a 0.2 % reduction in the total distance travelled.

In the context of the company's daily operations, using a cooling rate of 0.99 becomes unviable within the study's scope, encompassing a 30-day analysis. This is primarily due to the prolonged execution time of the employed methods. Conversely, the other two values demonstrate commendable performance while adhering to reasonable timeframes. This study analysed orders over a 26-day interval; nonetheless, optimal implementation of this methodology would entail daily algorithm runs to reconfigure routes designated by the WMS. This would ensure more efficient item collection operations daily. In such a scenario, execution times would remain within manageable limits compared to the prolonged durations of the present analysis.

Notably, these analyses were conducted using a computer with a seventh-generation Intel Core i7 processor and 16 gigabytes of RAM operating on the Windows 10 platform. Different computer configurations may yield divergent execution durations.

4.2. Findings

Considering the potential to reduce travel distance, thus reducing operating time, the method enables either reducing the number of operators, when technically possible, or increasing the capacity of the warehouse to provide and deliver orders and products.

In this case, the study revised about 15.3 thousand orders in a month timeframe. Considering the decrement of approx. 7 % of the distance, it would be possible to accommodate a demand of approx. 16.4 thousand orders.

Another crucial point to analyse is the issue of the area allocated for the picking sector. In this study, the picking sector had dimensions of 30 meters by 30 meters and the picking operation allocated nearly 250 pallet positions within the area.

In the examined warehouse, the picking department operates with 11 assistants, each responsible for approx. 9 % of the total distance travelled. The results may appear modest; nevertheless, they do not necessitate infrastructure investments and contribute to operational efficiency. This can ensure that the operation does not experience delays, colloquially referred to as "capote". Such delays occur when the process extends beyond the allocated timeframe, resulting in delayed departures of delivery vehicles. By implementing the proposed changes, all trucks can be loaded and ready to commence their routes in the morning. Furthermore, the reduction in the total distance travelled and a few other minor enhancements could reduce one operator, resulting in cost savings over a year.

Given that this company operates more than 100 distribution centres with picking operations, the impact of this tool's implementation across the network of warehouses could yield significant gains and substantial cost reductions, ultimately minimising wastage.

4.3. Warehouse-specific characteristics

Each distribution centre assumes responsibility for servicing a distinct region, subject to various factors like seasonality, localised marketing initiatives, negotiations with retail networks and partners, and several other variables. Consequently, each unit operates with varying average quantities of SKUs on the assembled pallets delivered to customers. In the case of the studied warehouse, this average is relatively low, as illustrated in Fig. 12, with an average of 7.21 different products on each pallet. This limitation reduces the potential for route exchanges and, subsequently, the reduction in distance. For instance, a pallet with only two different SKUs has only two route options: one "from A to B" and the other "from B to A". The larger the quantity of SKUs, the more

864442	**4**	**6**
P01_A_01_1/35	1	1
P01_M_01_1/35	1	1
P02_A_02_1/35	1	1
P02_M_02_1/35	1	3
864443	**38**	**295**
P02_A_02_1/42	4	42
P02_M_02_1/42	12	125
P03_A_03_1/42	15	63
P03_M_03_1/42	6	61
Z_Non_PALLETIZED_ITEM	1	4
864444	**56**	**377**
P01_A_01_1/42	12	85
P01_M_01_1/42	16	45
P02_A_02_1/42	4	9
P02_M_02_1/42	21	213
P03_A_03_1/42	1	12
P03_M_03_1/42	1	12
Z_Non_PALLETIZED_ITEM	1	1
864445	**28**	**185**
P01_A_01_1/42	1	20
P01_M_01_1/42	15	111
P02_A_02_1/42	3	3
P02_M_02_1/42	6	26
P03_A_03_1/42	1	12
P03_M_03_1/42	1	12
Z_Non_PALLETIZED_ITEM	1	1

Fig. 12. Dynamic orders

opportunities there are for algorithm-driven permutations, increasing the likelihood of finding shorter routes and significantly reducing the total distance.

Pallet assembly may involve more than 20 products in other distribution centres. In such cases, it is speculated that the benefits of employing the proposed methodology would yield even more significant results.

Conclusions

The methodology applied in this investigation has ascertained the feasibility of employing the simulated annealing algorithm within this context, reducing travel distance for operators. This inquiry was conducted at a distribution centre affiliated with a prominent beverage corporation in Brazil. A simulation model was adopted to obtain pertinent data about the spatial arrangement and the distances between each item's collection point to facilitate the algorithm's functionality. Furthermore, this model was deployed to authenticate that the alterations and computations enacted by simulated annealing led to a curtailment in the operators' traversal distance.

The examined warehouse manifests a scarcity of distinct SKUs per pallet, and the algorithm managed to effectuate a decrease of no less than 7.6 % in the traversed distance. In a warehouse characterised by a more heterogeneous assortment of orders and a larger volume of items, the benefits of this methodology could be more pronounced due to the augmented prospects for permutations in route sequences for each pallet.

The adoption of simulated annealing was substantiated by the diminishment in travel distances and the expeditious execution of computations within a relatively abbreviated time frame. A series of tests were administered to gauge the influence of the "cooling rate" parameter on distance reduction and execution duration. A modest value rendered results in under an hour, whereas a higher value necessitated more than five hours despite yielding considerably ameliorated outcomes. In a final test, the highest feasible value extended roughly 45 hours to converge towards a solution, delivering a mere 0.2 % enhancement compared to the antecedent scenario.

An additional salient consideration concerning the selected approach revolves around the impact of programming language choice on computational times. An expedited convergence could be attained by utilising a compiled language as opposed to an interpreted one, which was employed in this investigation.

The quantity of orders and assembled pallets can be considered a limitation of this study. Given the constraints of the current programming language, if it surpasses the quantity of orders presented in this study, it may take longer to converge. Another crucial point is acquiring real layout information from the picking area. If this process is inaccurately executed, it may compromise the accuracy of the findings.

In summary, the methodology advanced in this inquiry generates reductions in operator travel distances and exhibits versatility in its applicability across various distribution centres. This is contingent upon the availability of requisite data and input parameters.

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Early supplier involvement challenges in new product development projects: a bibliographic overview of lean production in the automotive industry

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ABSTRACT

The research is based on a literature review focused on early supplier involvement in new product development processes while working towards Lean production, especially for the automotive industry, where all actors must be fast and accurate. For practitioners, early supplier involvement is a topic that deserves serious attention since it impacts on decentralisation, promoting gains in quality, quantity, and execution time, as well as cost reduction and/or the acquisition of technical knowledge in developing products and production processes. The authors first introduce the key concepts, issues, and theoretical foundations concerning early supplier involvement challenges and new product development within organisations that affect their core processes and outsourcing strategies when seeking collaboration to develop more sophisticated technologies that a new product requires. The authors critically explore these issues, especially concerning earlier supplier involvement and its connection to the Lean philosophy, pursuing process tunning, considering production quantity, quality, and time, as well as avoiding penalising interruption within the automotive industry. The study provides the first critical review of potential challenges for a successful early supply involvement and, consequently, a successful new product development process decentralisation and the acquisition of technical knowledge in developing products and production processes needed to satisfy customers.

KEY WORDS

concurrent engineering, new product development, early supplier involvement, lean, production, automotive industry, feasibility

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Introduction

In today's competitive landscape, particularly in such industries as automotive, the imperative to accelerate time-to-market for new products is driving organisations to streamline their new product development (NPD) processes. This urgency arises from the need to swiftly seize market opportunities, enhance market share, and optimise returns on investments. The NPD represents a cornerstone of organisational success, encompassing the journey from generating new product ideas to transforming

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them into successful market offerings. Concurrent engineering (CE) emerges as a strategic approach, facilitating simultaneous design and development of all processes, with rapid access to pertinent information for informed decision-making. While NPD and CE have undergone continuous refinement over time to expedite series production, the integration of Lean product development (LPD) further enhances the NPD performance, leveraging CE as a key tool. However, amid these advancements, a notable gap exists in ensuring the feasibility of manufacturing processes for the final product, particularly when involving external suppliers. This critical concern underscores the importance of early supplier involvement (ESI), which seeks to bolster project feasibility, especially in external component manufacturing, through collaboration with suppliers possessing manufacturing expertise.

Furthermore, contemporary organisations increasingly outsource non-core processes to suppliers, capitalising on their cost advantages and technical proficiencies. As products demand increasingly sophisticated technologies, collaboration with suppliers becomes imperative to tap into specialised expertise, necessitating early supplier engagement in NPD processes (Stief et al., 2018; Pech et al., 2021). The central focus of this study is to explore the challenges associated with successful ESI implementation in NPD supported by CE, emphasising the pivotal role of ESI in enhancing NPD performance. This paper conducts a literature review to assess the relevance of ESI in current industrial contexts and evaluate its implementation while identifying associated challenges. Despite the abundant literature on supplier involvement in product development, quantitative studies linking this aspect with critical supply chain topics, such as risk management and information flow, remain scarce.

This paper follows a structured approach. Section 1 delineates the research methodology employed in this study, providing transparency regarding the adopted approach. Section 2 delves into a comprehensive literature review, exploring pertinent aspects of NPD and methodologies aimed at enhancing its performance. Key methodologies, such as Research and Development (R&D), Voice of Customer (VOC), and Design for Manufacturing and Assembly (DfMA), are examined, alongside critical insights into CE methodology for internal process enhancement. Additionally, LPD is discussed, offering insights into optimising the entire NPD process and introducing the pivotal role of supplier involvement. In Section 3, Results and Discussion, the focus shifts towards a detailed examination of supplier involvement, delving into the main challenges associated with its implementation. This section provides a nuanced understanding of the dynamics surrounding supplier engagement in NPD processes, paving the way for insightful discussions. Finally, the paper draws comprehensive conclusions regarding the NPD process and its implications for supply chain performance. Critical aspects driving the supply chain performance are highlighted, emphasising the imperative for organisations to evolve to effectively meet the diverse requirements of customers and end-users.

1. Research methods

Two methodological approaches were employed to conduct this study. First, a non-structured literature review identified the most relevant approaches affecting NPD and supplier involvement in this process. Next, a content analysis was performed on the selected documents from the literature review. A non-structured literature review is a technique for evaluating current literature on a specific topic without a pre-established framework or set of standards. Unlike systematic literature reviews, which follow a structured process with predefined search terms, inclusion/exclusion criteria, and data extraction methods, non-structured reviews offer a more flexible and exploratory approach. This method facilitates in-depth exploration of the subject, involving extensive reading and note-taking. Various sources, such as scholarly journals, books, conference papers, reports, and online databases, can be used to gather relevant information (Saunders et al., 2019).

This approach is particularly useful for exploratory research, where the primary objective is to comprehensively understand a specific subject, identify key discussions, and formulate hypotheses for future investigation. However, non-structured reviews may lack the reproducibility of structured reviews and are susceptible to researcher bias in the literature selection and interpretation. Therefore, researchers must maintain transparency in their methodology to minimise bias and ensure the reliability of their findings.

The limitations of unstructured reviews can be mitigated through a rigorous content analysis. Content analysis is a research method used to analyse qualitative data, predominantly text-based, to identify patterns within the data. This method involves comprehending the content in textual or visual resources, including interviews, articles, and other documents. Essentially, it is a systematic and organised technique for analysing information, allowing researchers to uncover insights that may not be readily apparent through qualitative or quantitative methodologies alone (Neuendorf & Kumar, 2016). The purpose of the applied research method was to investigate recent developments and innovations in NPD, CE and LPD tools and methodologies, particularly focusing on how these advancements improve results and performance. Additionally, the research aimed to examine the extent to which these methodologies incorporate ESI as an integral part. This investigation was especially pertinent to understanding the role of ESI in enhancing the feasibility of projects, particularly during their initial phases. In summary, ESI is typically included in NPD only when the article specifically focuses on ESI. NPD, CE, and LPD methodologies generally emphasise client relationships to a lesser extent, particularly during the early stages of a project.

The literature review was conducted using published studies from the Scopus and Web of Science databases, focusing on the challenges of ESI in NPD projects. The review involved a series of sequential searches to refine the results based on specific inclusion and exclusion criteria. The search utilised a set of keywords: "NPD", "CE", "LPD", and "ESI", looking for their occurrence in the "Article title", "Abstract", and "Keywords" fields. There were no time frame restrictions, allowing for an examination of how the topic has evolved over the years. The inclusion criteria comprised documents from international journals and conference proceedings written in English. The search yielded a total of 150 documents. These selected documents were then subjected to a descriptive analysis.

2. Literature review

This section presents the most relevant approaches from the literature supporting the NPD process, mainly the CE and LPD. This literature review aims to show that topics such as NPD, CE, and LPD always present innovations and new methodologies to help/support the organisation launch a product aligned with customer/society expectations. However, the scope of innovations focuses on improving performance in the stages that, in most cases, still occur within the organisation, almost always upstream of the industrialisation phase of the individual components (external suppliers) and the final product (organisation). Normally, these innovations do not reflect improvements in the industrialisation process to guarantee a validation phase without any problems (or minimal) and, consequently, to avoid delays in the agreed deadlines.

2.1. New product development

Organisations universally recognise the importance of refining the NPD process to ensure each new product's successful and timely launch. This process typically comprises five distinct phases, beginning with opportunity identification, which detects market or technology gaps, then concept development, product design, process design, and concluding with commercialisation and product launch (Kowang & Rasli, 2011). However, despite these efforts, Cooper (2019) presented sobering statistics indicating that many new products fail to achieve commercial success. Of every seven to ten new product concepts, only one emerges as a commercial success, with only 13 % of companies meeting their annual profit goals from new product efforts. Cooper outlined twenty critical drivers of success, categorised into tactical, business-level, and systemic factors, emphasising the need for a comprehensive strategy to drive successful NPD outcomes.

Notable among these drivers are "VOC: Building the voice of the customer" and "Quality of execution", highlighting the importance of customer involvement throughout development and the need for flawless execution to minimise waste (Cooper, 2019).

Thompson et al. (2018) and Tai (2017) delved into the critical aspects of NPD from complementary perspectives. Thompson and colleagues emphasised the pivotal role of DfMA in minimising late engineering changes (ECs) and optimising time-to-market efficiency. Their research underscored the importance of integrating production considerations early in the process and leveraging CE to enhance productivity and product quality. Additionally, they proposed using key performance indicators (KPIs) to continually monitor and refine NPD processes (Thompson et al., 2018). Concurrently, Tai (2017) shed light on the evolving NPD landscape, stressing the increasing complexity of interorganisational collaborations and the growing importance of information technology (IT) solutions like product lifecycle management (PLM) systems. The research advocated for the strategic use of PLM systems to streamline workflows, facilitate resource coordination, and effectively harness external knowledge. Companies can achieve superior NPD performance in today's dynamic market by focusing on process management capabilities and aligning activities with PLM systems (Tai, 2017).

Melander & Lakemond (2015) highlighted the crucial role of supplier collaboration in navigating technological uncertainty and fostering innovation in NPD projects. They advocated for collaborative initiatives that unite buyers and suppliers, leveraging their combined expertise to drive product development. Despite the challenges posed by technological unpredictability, collaborative projects offer opportunities for dynamic adaptation while mitigating risks through strategic organisational separation (Melander & Lakemond, 2015). These insights underscore NPD's dynamic and multifaceted nature, emphasising the importance of strategic foresight, organisational agility, and collaborative partnerships in driving innovation and securing sustainable competitive advantage in today's rapidly evolving marketplace.

Liu (2019) delved into R&D internationalisation and NPD recentralisation, highlighting the importance of understanding the dual functions of R&D: research and development. While research generates scientific achievements and patents, development drives new product innovation. However, patented knowledge may not translate into profitable innovations without proper NPD practices. R&D internationalisation involves creating or acquiring R&D centres abroad, often leading to a decentralised structure initially. Yet, as the number of autonomous R&D units grows, coordination challenges emerge, prompting recentralisation for better control and knowledge leverage on a global scale. These recentralisation processes are unprecedented in R&D internationalisation. Cheng & Yang (2019) investigated the relationship between creativity processes and new product performance, which is crucial for competitive advantage. Innovation stems from organisational creativity, with employee engagement in the creative process (CPE) playing a vital role. CPE involves problem identification, information search and encoding, and idea generation, which can overlap to expedite NPD. The study provides a comprehensive model connecting creativity research with NPD outcomes, highlighting the importance of CPE components as antecedents of new product performance. Moreover, it identifies NPD speed as a critical mediator in the relationship between CPE and new product performance.

Zhang and Min (2019) focused on knowledge hiding (KH) in NPD project teams, distinct from knowledge sharing, which poses challenges to team performance. While knowledge is essential for organisational sustainability, KH impacts project team performance negatively, mediated partially by team learning. KH often occurs in NPD project teams, hindering performance. The study based on data from 92 NPD project teams in China revealed a negative association between KH and project team performance, moderated by team stability. As team stability increases, the negative impact of KH on project team performance weakens, emphasising the importance of knowledge sharing within NPD teams.

Further, Waal & Knott (2019) investigated how small high-tech companies utilise tools to support their NPD activities. Their mixed-methods approach began with a survey of 99 companies, examining 76 tools across 12 functional perspectives on NPD, revealing significant variability in the considered scope. Addressing the prevalence of variability in tool use rigour and its drivers, the study sheds light on the differences between small and large companies in their approach to business processes and innovation systems.

In contrast, Chang (2019) delved into the realm of customer engagement during the NPD phase, analysing its impact on new product market performance. Their research scrutinised the synergistic or detrimental effects of engaging customers across different NPD stages. While traditional wisdom suggests engaging customers in distinct stages, Chang's findings indicate that simultaneous engagement across multiple stages yields more favourable outcomes. Particularly, involving customers in the ideation and development phases fosters synergistic effects by integrating customer knowledge into product ideation. However, relying solely on internal interpretations of customer data may limit its effectiveness. Ultimately, Chang's study underscores the importance of strategic customer engagement throughout the NPD process for optimal market performance.

2.2. Concurrent engineering

In the context of CE, the fundamental principle guiding the development of new products, known as NPD, is the comprehensive consideration of all aspects of a product's lifecycle right from the project's inception. CE was initially introduced in 1988 by the Institute of Defence Analysis (IDA), signifying a paradigm that involves designing a product simultaneously with its downstream production and support processes (Zidane et al., 2015). Unlike the traditional sequential development approach, CE fosters parallel work-in-flow activities within the NPD process, encouraging the simultaneous advancement of various project components. For instance, product design and planning activities can proceed concurrently, allowing for integration with production planning and control or even initiating product planning before finalising the concept. While this approach does not shorten the duration of individual activities, it effectively reduces the overall development timeline. Moreover, the parallel nature of work facilitates seamless information exchange among stakeholders, minimising unforeseen errors and the need for corrective actions later in the development process (Valle & Vazquez-Bustelo, 2009). At its core, CE embodies a holistic engineering and management philosophy addressing product lifecycle concerns, with its most notable aspect being the adoption of multidisciplinary and cross-functional team structures (Shouke et al., 2010). Organisations implementing CE have witnessed tangible improvements in various performance metrics, such as quality, cost, and time. Some reported benefits include reductions of 30–60 % in time-to-market, 15–50 % in lifecycle costs, and 55–95 % in engineering change orders (Fine et al., 2005). CE relies on three fundamental elements to realise such objectives: simultaneous workflow, timely involvement of all relevant stakeholders in product development, and fostering a collaborative teamwork environment (Koufteros et al., 2001; Valle & Vázquez, 2009). The typical image of CE implementation is the simultaneity obtained by how tasks are scheduled and the interactions between the different actors (people and tools) in the product development process.

A second aspect is the integration and/or relationship between the process and the information/knowledge content happening "between" and "within" the project stages, considering all the technologies and tools used in the product development process (Zidane et al., 2015). The dynamics of technological advancements and market shifts often introduce uncertainties and complexities into product development, prompting companies to explore structural adaptations to enhance their competitiveness. CE emerges as a potent mechanism for mitigating uncertainty and improving organisational agility (Koufteros et al., 2001). A crucial aspect entails early requirements analysis by multidisciplinary teams and careful consideration of all lifecycle aspects affecting a product, facilitating integrated concurrent design (Zidane et al., 2015). By addressing lifecycle issues upfront, projects can achieve a "right the first time" outcome, leading to cost savings and accelerated product development, sometimes by up to 70 %, while precisely meeting customer needs (Sapuan & Mansor, 2014).

Furthermore, implementing CE necessitates organisational changes spanning manufacturing techniques, quality management, market strategies, and employee mindsets. Such adaptations enable handling complex products while maintaining high quality, achieving accelerated deliveries, and reducing manufacturing costs, with approximately 80 % of production costs attributed to the design phase. This strategic readiness equips organisations to swiftly respond to evolving market demands and reduce time to market (Zidane et al., 2015). CE implementation typically unfolds through two approaches: team-oriented CE and IT-centric CE, particularly, CE-oriented and knowledge-based engineering (KBE) (Sapuan & Mansor, 2014).

Leveraging computer tools and technologies, such as the Pugh concept selection matrix and Pugh total design approach, aids in expediting the CE process, streamlining cycle times, and ensuring comprehensive product design management (Sapuan & Mansor, 2014). Additionally, simultaneous engineering offers a strategic framework to compress the time-to-market for new products, facilitating swift market entry, even amidst simultaneous NPD processes.

Nelson et al. (2016) advocated adopting the Graphical Evaluation and Review Technique (GERT) to address complexities in concurrent NPD, including bidirectional project interdependencies and resource limitations. Originating from Drezner and Pritsker (1965), the GERT model provides a robust platform for estimating project completion times by accounting for dynamic information flows and coordination complexities within concurrent NPD processes (Nelson et al., 2016). Its graphical representation aids in visualising communication and information flows, offering managers a comprehensive understanding of the NPD process dynamics.

Assessing the progress of CE implementation within companies is crucial for enhancing efficiency and effectiveness. Karningsih et al. (2015) investigated CE implementation in Indonesian companies, utilising the Simultaneous Engineering Gap Analysis (SEGAPAN) checklist and Analytical Hierarchical Process (AHP) for evaluation purposes. The study aimed to quantify the level of CE implementation, identify implementation difficulties, and provide a case study on CE implementation in the context of the Asian/Indonesian industry. SEGAPAN comprises six domains: management role, corporate culture, cross-functional teams, co-design, communication infrastructure, and tools and techniques. Each domain encompasses multiple factors, with AHP utilised to quantify the weight of each factor in the CE implementation compliance domain. The CE rate, classified into three levels (excellent, average, and poor), gauges the extent of CE implementation within a company. The study revealed that although Company X achieved an excellent level of CE implementation, three impediments hindered further progress: inadequate management role, resistance to cultural change, and insufficient cross-functional team collaboration. These challenges stemmed from senior management's limited understanding of CE implementation, exacerbated by a lack of clear implementation strategy and structure dating back to the financial crisis of the 1990s. Company X plans to address these issues by restarting the CE implementation using a well-structured strategy, possibly employing the Change Acceleration Process (CAP) approach. Additionally, Company X commenced implementing Lean Manufacturing (LM) in 2013, aligning with CAP steps, including CE training, knowledge sharing, and recruitment process modifications (Karningsih et al., 2015). Similarly, Ganagambega & Shanmugam (2012) assessed CE utilisation levels in Malaysian small and medium-sized enterprises (SMEs) through supplier surveys. Despite a lack of understanding of CE concepts, most Malaysian SMEs embraced CE principles in their NPD processes. The study highlighted the importance of effective communication and workforce competence, emphasising training and motivation to enhance product development team skills. Ganagambega & Shanmugam (2012) proposed developing user-friendly, rapid application methods to promote CE adoption in SMEs and advocated for increased awareness and education through training initiatives. These efforts aim to facilitate the integration of CE practices into SME operations, fostering innovation and competitiveness in the marketplace.

2.3. Lean product development

LPD is particularly important during the product design phase and naturally has implications for production. The focus on LPD is based on the challenges in (i) managing the development of new sustainable products that offer value to customers, (ii) reducing time to market, and (iii) the efficient use of resources (Sousa & Dekkers, 2019). LPD is a product development method that uses Lean principles and focuses on reducing waste, accelerating delivery, and increasing profit and customer value. According to the literature, Lean principles should not be applied in manufacturing only but should also be extended to other processes, especially those further up the production chain, such as the product development process (PDP), which has great opportunities for applying these principles. It is important that the product is developed based on Lean principles, so that possible waste from the PDP is avoided at the time of manufacture. LPD involves applying Lean principles learned in LM and Lean practices specific to product development in the PDP (Pinheiro & Toledo, 2016).

LPD handles the complete process from collecting and generating ideas, going through evaluating the potential for success, developing concepts, evaluating them to create the best concept, detailing the product, testing/developing it, and delivering it to manufacturing (Mynott, 2012; Rauch et al., 2017).

Table 1 highlights the trends in developing new products in the automotive industry in recent decades. As of 2010, the trend is towards the product development process according to the Lean methodology. It has focused on "innovation" and "feasibility". Therefore, the customer's expectations regarding the product, the customer focus, the "value" or "price" that the customer attaches to that product and the function of the product have emerged in the current social and economic context. "Lean tools" in the value stream, therefore, "Lean management" in the final product, includes important issues and interdisciplinary approaches (Paker, 2021).

LPD, akin to LM, emphasises innovation and the development of new products, albeit with distinct foundational principles. Dombrowski & Schmidtchen (2014) provided a comprehensive overview of key Lean methods in product development, categorising them into seven fundamental principles (Fig. 1). In the automotive sector, the efficacy of the LPD process is gauged by the efficiency of the value stream and the global market penetration of the final product. Consequently, identifying and eliminating non-value-adding elements or processes are paramount, as are those that encumber the system (Paker, 2021). An essential tenet of the LPD process involves the eradication of activities that fail to contribute value, thereby mitigating waste.

Tab. 1. Trends of NPD in the automotive industry

Phase	Period	Focus on	Management of organisation	Technology	Tools/methods
Industrial age	1850	- Specialisation	- Functional Hierarchy	- Mechanisation	- Scientific management
Information age	1908	- Productivity performance - Cost reduction	- Line production - Order/Controls	- Serial production - Standardisation - Data storage	- Task specialisation - Financial Modelling
1st wave: Sequential Process	1970	- Quality management - Continuous flow - Task efficiency	- Diversification of companies - Fusions and acquisitions	- Automation information - Technology management	- Total quality management (TQM) -Statistical process control - Process improvement methods
2nd wave: Concurrent process	1990	- Process innovation - Best practices, faster - Business over the Internet	- Flat organisations - Value added for customer operational excellence	- Enterprise Architecture - Enterprise Resource Planning (ERP) - Customer Relationship Management (CRM) - Supply chain management	- ABC analysis - Six Sigma - Process redesign - Methods of reengineering
3rd wave: Process management	2000	- Adaptability agility	- Network-centric organisation - Hyper-competition	- Enterprise - Application integration - Architecture oriented on services	- Balanced Scorecard (BSC) - BPM systems - Outsourcing
4th wave: Lean culture	2010	- Continuous change - Dissipate - Muda	- Market growth - Process effectiveness before efficiency - Poke-yoke - Fix right the first time	- Performance management software - Business Process Management (BPM) Systems	- Outsourcing - Project field - Communication discipline - A3 contact (Lean)

Source: Elaborated by the author based on (Paker, 2021).

Companies must prioritise learning and effectively implementing value stream techniques and LPD strategies to enhance their competitiveness and pinpoint and eliminate waste within their business value streams. In the automotive industry, it is crucial for companies to assess their current position and future direction regarding the simplicity of their value stream, remaining adaptable to drive continuous improvement (Paker, 2021). Another critical focus area is applying Lean methodology in NPD, particularly in small and medium-sized enterprises (SMEs). Rauch and colleagues (2017) shed light on the limited research surrounding the adoption of Lean in the R&D departments of SMEs. Their study offers a unique evaluation of the applicability, benefits, and critical factors of LPD for SMEs, drawing insights from a survey conducted across 54 SMEs in Italy (Rauch et al., 2017). Furthermore, their research explores the impact of emerging Industry 4.0 techniques on product development and how they may influence the efficacy of Lean practices within this domain.

The primary findings underscore the swift introduction of several Lean methods, offering substantial potential for improvement, especially when combined with Industry 4.0 technologies, which serve as catalysts for enhancing efficiency in product development (Rauch et al., 2017). Another notable application of Lean methodology is within the supply chain. While manufacturers readily embrace Lean development principles, suppliers often struggle to align with these methodologies. Research by Dombrowski & Karl (2017) highlighted the limited applicability of these methods and principles to suppliers, attributed to differences in process structure and specific tasks. Although their study was based on subjective evaluations through expert interviews, it concluded that the Lean development system must be tailored to suit the specificities of SMEs. Their findings offer valuable insights for adapting the Lean development concept to SMEs, emphasising the need for tailored approaches. Certain principles, methods and tools vary in relevance for SMEs, requiring careful consideration and adaptation. For instance, principles such

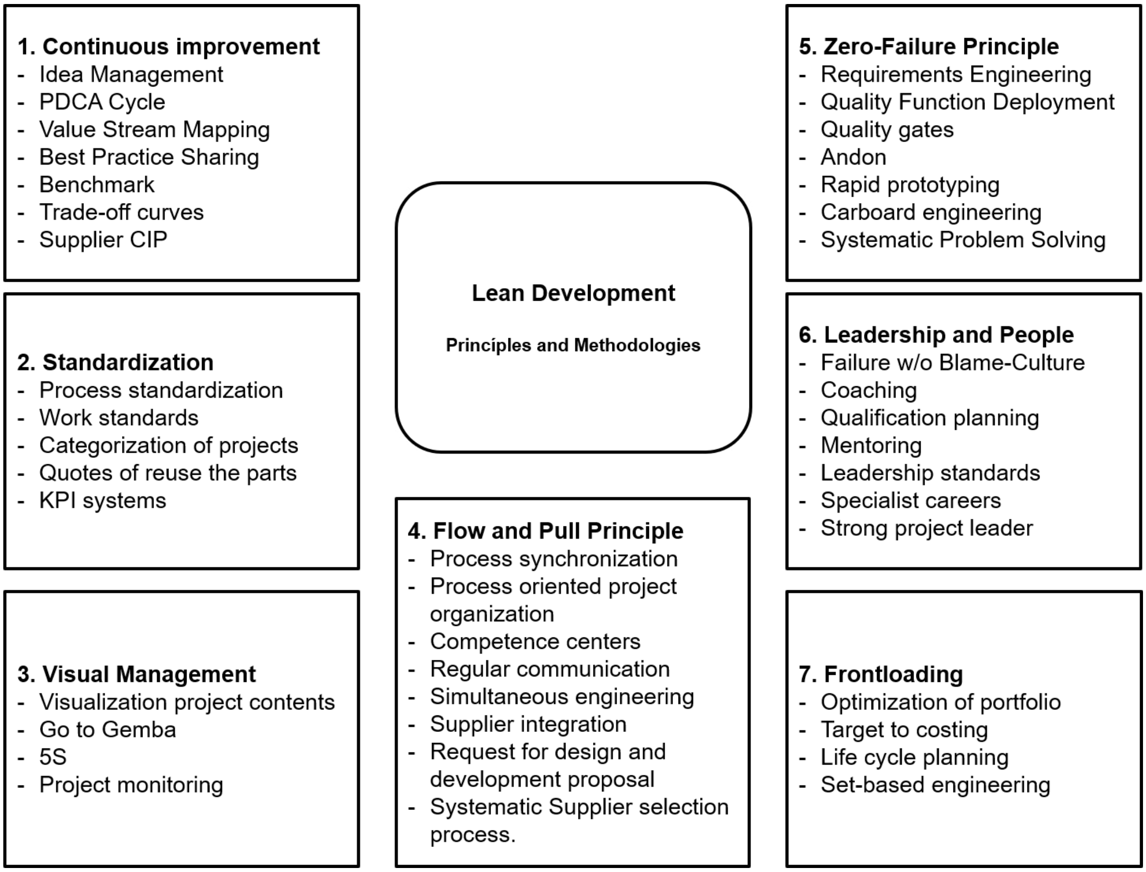

Fig. 1. Lean product development principles and methods

Source: Elaborated by the authors based on (Schmidtchen, 2014).

as standardisation, zero defects, and anticipation must be systematically integrated into Lean development systems for SMEs to ensure effective implementation and success.

The discussion continues on the discourse around sustainability, sustainable products, and sustainable product development. A systematic literature review conducted by Souza & Dekkers (2019) explored existing LPD methods and tools to assess their contributions to sustainability. The findings suggest that while there is no shortage of methods and tools, their practical application is lacking. From a sustainability perspective, most tools and methods predominantly focus on economic and environmental dimensions, with only a few encompassing the social dimension or addressing all three dimensions collectively (economic, environmental, and social). Given that sustainability inherently integrates economic, environmental, and social aspects, understanding their interdependencies emerges as a critical issue warranting further attention from researchers. Thus, a deeper reflection is needed on how these methods and tools can effectively contribute to each dimension of sustainability. Additionally, the review identified certain limitations, such as the scant exploration of potential conflicts, synergies, or overlaps between LPD and sustainability in literature and practice. While practices may be designed with sustainability in mind, they often fall short of embracing the holistic concept of sustainability.

3. Results and discussion

This section discusses the main insights concerning the challenges of ESI in NPD projects.

3.1. Importance of ESI in NPD projects

The significance of supplier involvement in NPD projects is increasingly recognised as product lifecycles shorten and technological advancements become more sophisticated. Companies often focus on their core processes while outsourcing others, leveraging potential cost advantages or tapping into suppliers' technical expertise in product development and production processes. As products become more technologically complex, organisations rely more heavily on supplier collaboration to ensure access to the necessary technologies required to meet customer demands. Consequently, NPD processes often span the supply chain, reflecting a decentralised approach. Supplier involvement programmes are generally viewed favourably in NPD endeavours, offering benefits such as enhanced product quality, reduced time to market, and lower development and production costs (Ramanathan, 2014). Addressing technological uncertainty emerges as a pivotal aspect of supplier integration research. Studies suggest that sharing costs, information, and technology with suppliers can mitigate technological uncertainties. Organisations frequently partner with key suppliers to steer technology development efforts and drive cost reductions in response to such uncertainties. However, in the context of production chains, integration tends to be more standardised, and the degree of supplier involvement may have less bearing on process success (Bornia & Lorandi, 2008).

Fostering effective interaction within the supply chain requires understanding the characteristics and nuances of partners, particularly suppliers, in terms of organisational structure, cultural aspects, and technological competencies. The nature of the relationship established at the supplier-organisation interface in NPD significantly impacts performance (Bornia & Lorandi, 2008). First-tier suppliers encompass various configurations: (1) "Partner to Risk Sharing" involves one company associating with another to coordinate development and share risks under long-term contracts. The partner is deeply involved in all NPD stages. (2) "Technological Partner" entails technology transfer, often from suppliers or machine suppliers, especially when their technology is a differential or through universities and research centres. (3) "Co-Developer" refers to a supplier participating in defining subsystem requirements and development, actively contributing to the design team and final product specification. Second-tier suppliers, termed "Service Providers", receive product requirements and specifications from the customer (organisation) and develop tailored solutions (Bornia & Lorandi, 2008).

Lastly, "Standard Parts Suppliers" focus on timely and cost-effective delivery, particularly for commodities that are not strategically vital to customers, often selling products through catalogues (Bornia & Lorandi, 2008). Eisto et al. (2010) delineated collaboration levels between the organisation and the supplier, starting with the "Order Delivery Level" (Level I), where the organisation contacts suppliers upon project completion. Initial contact typically involves a request for quotation, with part designs and related components mostly finalised. Minor adjustments may be feasible, such as wall thickness modifications or draft additions for castings. The organisation compares quotations from multiple suppliers before selecting one, providing delivery dates. ESI is not used at this collaboration level (Eisto et al., 2010).

In the "Cooperative Level" (Level II), organisational and supplier processes partially overlap, fostering cooperation in design. Suppliers can provide feedback and assess part designs before finalisation, enabling adjustments to simplify manufacturing processes. Contracts gain significance at this stage as suppliers contribute to enhancing the organisation's component designs, leveraging their resources for improvement (Eisto et al., 2010). At the "Partnership Level" (Level III), suppliers are engaged at the project outset, and processes fully align. This alignment allows each supplier's expertise to be strategically applied to the organisation's project at the appropriate juncture. This level is well-suited for intricate or critical parts of the final product. Instead of prioritising the lowest quote, partners collaboratively innovate value-added solutions. Such innovative solutions offer greater long-term cost and time reductions compared to price-driven competition, optimising both the product and production chain (Eisto et al., 2010). Simulations exemplifying collaborative approaches between organisations and suppliers aim to gain deeper insights into potential part-filling outcomes during the initial NPD phase. Interpretation of simulation results allows users to propose design changes or die-casting system modifications, which are particularly effective when executed in the product design phase before finalisation. Conversely, making such adjustments after the design is frozen limits process parameter alterations and forfeits opportunities for enhancing manufacturability.

Another significant aspect concerns supplier selection. Giuseppe & Calabrese (2018) introduced additional criteria gaining relevance, focusing on the impact of reputation on supplier selection within the European automotive industry, particularly among Tier 1 suppliers. Their empirical approach involves detailed descriptions of strategies and databases, drawing data from purchase contracts in the European automotive components market. Their findings underscore the critical role of reputation, suggesting that suppliers serving diverse customer bases or those heavily engaged with premium brand customers stand better chances of securing additional orders and expanding their customer portfolio, including non-premium customers, in subsequent periods (Manello & Calabrese, 2018). This perspective aligns with Schoenherr and Wagner's (2016) proposition regarding supplier involvement in the fuzzy front end of NPD. In a dynamic market that prioritises "faster, better, and cheaper" products, innovation becomes imperative for maintaining competitiveness. This necessitates increased supplier and customer involvement, particularly in NPD endeavours. The core concept is to engage suppliers as early as possible in the NPD process, particularly during its initial phase — idea generation, refinement, product definition, and project evaluation, collectively termed the "fuzzy front end" (FFE) of the NPD process. Despite its criticality, FFE is often characterised by poorly defined processes, ad-hoc decisions, errors and uncertainties, with limited emphasis on supplier involvement. The proposition here emphasises the perspective of social exchange theory (SET) since supplier involvement in NPD involves a social exchange. SET proves valuable in exploring company relationships by offering deeper insights into underlying dynamics and tapping into significant social relationship components like homophily and benevolence (Schoenherr & Wagner, 2016).

Environmental concerns and supplier involvement in green supply chains hold significant relevance in today's landscape. Pressing issues like climate change and biodiversity loss demand urgent responses. Also, consumer demand for eco-friendly products is growing, prompting stricter environmental regulations over time. Caniels et al. (2013) aim to elucidate the factors driving supplier participation in green supply chain initiatives. They propose a conceptual framework delineating supplier involvement driver, including customer requirements, supplier readiness, relational norms, and client influence. Essentially, this initiative calls upon companies and suppliers to embrace sustainability practices. Delayed action on this front makes it increasingly challenging for suppliers to adapt their production processes and bolster their knowledge base to assume leadership in "green" production.

Furthermore, it hampers their market competitiveness vis-à-vis existing suppliers who are already well-versed in sustainable practices, necessitating substantial investments from new entrants to level the playing field. Notably, the image and public perception of an automotive original equipment manufacturer (OEM) regarding corporate social responsibility (CSR) hinge not only on its own CSR performance but also on that of its supply chain members, particularly its suppliers, given the OEM's responsibility for the sustainability of the entire chain (Caniels et al., 2013). In a separate study, Ghadimi et al. (2017) proposed a fuzzy inference system based on an audit checklist to assess supplier sustainable performance comprehensively. This system considers all facets of sustainability, providing a practical framework to evaluate and select the most sustainable suppliers. It was applied to select sustainable suppliers at a French automotive parts manufacturer licensed under a French automotive organisation. The objective was to evaluate potential suppliers accurately and facilitate informed decision-making. The collected data was processed using the proposed fuzzy inference system to mitigate inaccuracies, ultimately presenting a ranking of suppliers with less uncertain sustainability performance scores, enabling reliable sourcing decisions. Although this approach may be generic, the formulation of sustainability criteria and sub-criteria must be aligned with the specific sector, in which a company operates. Consequently, criterion sets must be adapted for other analyses to ensure proper functionality (Ghadimi et al., 2017).

3.2. Challenges in the application of ESI

The known fragility concerning the ESI applied in the NPD is based on the few available studies. They typically consider various NPD decisions of a single organisation, including product positioning, CE, and common components (Ramanathan, 2014). Studies investigating the NPD with ESI application consider, as conflicting issues, the balance of the main decision variables (project quality, quality of compliance, and ESI extension) in relation to internal and external environmental conditions. Partitioning product development processes along the supply chain — when applying ESI — produces a wide variety of transactional externalities and inefficiencies as the level of supplier involvement increases and the technologies

Tab. 2. Summary of the challenges in the application of ESI

Challenges	Main topics	Reference
The impact of supplier involvement in product development on supply chain risks and supply chain resilience	Identifying dependencies between Supplier Involvement Product Development (SIPD), risk and supply chain resilience; a lack of valid and reliable measurement models.	Wieteska (2018)
Lack of an easily applicable tool to assess the quality of a proposed innovation and the quality of the supplier that proposed the idea	Supplier innovation may also imply a high level of dependence of a buying company on its innovative supplier, representing a potential risk for a buying company by (a) risk of supplier incompetence in project execution and (b) supplier resource dependence for its innovation capacity and a denial of access to these.	Goldberg & Schiele (2018)
Effect of uncertainty, supplier involvement, supplier performance, and partnership quality on buyer-supplier relationship	Evaluate how the relationships between firms and suppliers will affect the supply chain of manufacturing and non-manufacturing companies, especially the effect of uncertainty, ESI, supplier performance, and partnership quality on buyer dependence on the supplier.	Mudasser et al. (2022)
NPD processes are often decentralised in the supply chain	Develop analytical models to shape the NPD project environments in which the organisation must engage in cooperation with its suppliers.	Ramanatha (2014)
Effect of ESI on firm performance through teamwork and NPD	It is important to have a proper insight into manufacturing management to understand how ESI affects teamwork, new product and development. It is observed that teamwork affects NPD and firm performance. Moreover, NPD affects firm performance. In addition, ESI indirectly affects firm performance through NPD and teamwork, respectively and simultaneously.	Oktapia et al. (2022)
The suppliers may be reluctant to make huge/continuous product-specific (and/or manufacturer-specific) investments due to a lack of incentives and bargaining power	NPD characterised by weak-defined product requirements, unreliable demand forecast, unproven production technology and significant up-front costs, which brings considerable risks on developing new products with strong strategic implications but modest financial payoffs in the short-run. The firm can potentially mitigate by engaging suppliers with proven know-how, knowledge, expertise, and capacities, but how long can the supplier afford to explore promising leads for radical innovations and how much design effort should be allotted to the project?	Chiang & Wu (2016)
ESI requires a continuous information flow supported by robust information systems that can ensure data availability and reliability as well as information and knowledge confidentiality to chain members	Information systems provide a high integration level, which is not possible among supply chain members since companies use different systems, obstacles arise from distinct system structures, such as application languages and databases, and management systems not being compatible with each other; this generates further manual activities that render data exchange more complex and less accurate. Information systems, such as ERP, positively impact product quality improvement, development time reduction and cost gains, increasing sector competitiveness, especially because these systems allow faster information sharing among chain members.	Junior et al. (2019)
NPD environments typically have high levels of technological uncertainty	It is a key variable in research involving supplier integration. Technological uncertainty can be reduced by sharing costs, information and technology. Organisations often team up with their key vendors to influence the direction of their technology development and cost reduction efforts.	Bornia & Lorandi (2008)
Perception of CSR	The image and public perception of an automotive OEM with regard to CSR does not only depend on its own CSR performance but also on the CSR performance of its supply chain members, in particular its suppliers, since the OEM is responsible for the sustainability of the entire chain.	Caniels et al. (2013)
The influence of reputation on supplier selection in the automotive industry	Especially in the European automotive industry, suppliers (a) who serve a diversified customer base or (b) with strong exposure to premium brand customers have better chances of obtaining additional orders and expanding their customer base even further, consequently winning more orders also from "non-premium" customers in the subsequent period.	Manello & Calabrese, 2018

required become progressively more sophisticated. Table 2 compiles the main challenges faced in implementing ESI more robustly, considering the literature review densely explored in this paper.

Conclusions

The article underscores the significance of internal processes within organisations, particularly focusing on key methodologies like NPD, CE, and LPD. These methodologies aim to boost performance and facilitate successful product launches within specified timelines. However, the analysis reveals a gap in the depth of industrialisation phases associated with these processes, particularly when organisations face challenges due to insufficient technical knowledge for developing complex products and production processes. In today's competitive landscape, organisations, especially in sectors like automotive, confront the urgent need to swiftly introduce innovative products to the market.

NPD, especially when incorporating new technologies, demands more efficient responses to meet customer/end-user requirements. To achieve this, organisations must tap into resources from the supply chain to address internal gaps, expedite time-to-market for customised products, meet deadlines, and enhance customer satisfaction.

A critical aspect highlighted is the adoption of techniques such as decentralisation of the NPD process, with a focus on ESI, to acquire crucial technical knowledge essential for complex product and production process development. ESI plays a pivotal role in successful decentralisation, leading to quality enhancements, reduced execution time, and cost savings. Moreover, the article conducts a thorough analysis of ESI challenges and their impact on NPD within organisations, particularly regarding outsourcing strategies and collaboration with external partners. It underscores the significance of ESI for process optimisation, ensuring production quantity, quality, and timely delivery, thus averting disruptions in the automotive industry.

Furthermore, the paper provides invaluable insights into NPD, especially in scenarios involving external partners in the supply chain. It identifies opportunities to address emerging process requirements and offers an initial review of potential challenges for successful ESI. Ultimately, integrating ESI with Lean production approaches can mitigate issues during mass production, driving efficiency in product development processes.

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Sustainability reporting in selected automotive companies

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ABSTRACT
The benefits of sustainability reporting are indisputable. These include, first and foremost, building trust. Transparency on non-financial performance can help reduce reputational risk and open a dialogue with stakeholders. Transparent sustainability reporting is also a sign of openness and responsibility. Efforts to develop the economy sustainably include the development of reporting concepts in this sphere. Sustainability activities are becoming an increasingly important element of business reports. This article aims to present and verify the current sustainability reporting at the level of comparison of reported indicators of selected automotive companies in the context of the most widely used Global Reporting Initiative systematics and the upcoming requirements defined by the Corporate Sustainability Reporting Directive (CSRD). It focuses on study cases and identifies good practices and difficulties of sustainable reporting in the automotive industry. This study used the case study method on selected automotive industry companies. The case study analyses a defined problem consisting of a real situation and information as a methodological tool. The findings show that the world's major automotive companies are broadly endeavouring to realise sustainability practices. The main conclusion of the analysis is that the Environmental, Social, and Governance (ESG) framework and the Global Reporting Initiative (GRI), in addition to being complementary, can be combined not only to improve the strategic management of an organisation but also, in a broader context, serve the well-being of the local community and society at large. The article organises and systematises knowledge about the ESG concept and the GRI standard, which currently play an important role in sustainability reporting.

KEY WORDS
ESG (social, environment and governance), GRI, Global Reporting Initiative, sustainability, reporting of sustainability matters

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Introduction

Reporting on sustainability activities is becoming an increasingly important element of reports presented by companies. Contractors, investors, and consumers appreciate the organisation's attention to issues beyond economic performance, such as environmental issues and activities in the area of social responsibility. This increases their confidence in the company, making them more inclined to cooperate with a particular enterprise or to choose its products or services.

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With the increasing prevalence of non-financial issues, which are often treated on a par with financial performance, a number of benchmarks for reporting sustainability-related indicators have been developed, and one of the most common is the Global Reporting Initiative (GRI) or global best practices for organisations to communicate and demonstrate accountability for their environmental, economic and human impacts. GRI systematics has been used voluntarily by companies for 26 years. However, the EU is now on the threshold of introducing mandatory reporting of sustainability activities according to the principles described in Directive 2022/2464 of the EU Parliament and the Council of December 2022 as regards corporate sustainability reporting (CSRD).

Some organisations report on non-financial indicators in advance, often using the GRI standard, as exemplified by some automotive companies among the world's largest vehicle manufacturers. Considering the above, this paper aims to compile current sustainability reporting and attempts to answer the following research questions:

- What is the interplay between ESG and GRI?
- To what extent can reporting based on the GRI systematics be used to report ESG indicators according to the CSRD in the automotive industry?

It also aims to verify current sustainability reporting at selected automotive companies: VW Group, Ford Motor Company, and MAN Truck & BUS SE.

The first part of the article, which is this introduction, is followed by a description of the main findings from the literature study relevant to the purpose of this article. This part describes the ESG concept with particular reference to the GRI reporting standard and its impact on business development.

The next sections describe the research methods and results of the current approach to reporting sustainability indicators in selected automotive companies without comparing the indicator values, broken down into environmental (E), social (S) and corporate governance (G) indicators. Next, the results are discussed, and the article concludes with conclusions.

1. Literature review

The ESG concept is one of the biggest changes currently confronting businesses, and it will become even more important in the future. Globally, companies are adopting ESG measures to stay competitive in the dynamic environment (Yadav & Prashar, 2022). The ESG concept originated in finance in the 1970s, when a small group of investors took an interest in the environmental and social practices of the companies they invested in (Galbreath, 2012). Environmental (E), social (S) and governance (G) factors are considered when measuring the sustainability and impact of an organisation (Table 1).

Environmental factors refer to how the organisation uses renewable and non-renewable resources, including the amount and type of energy used, greenhouse gas emissions, the amount of waste generated and how it is disposed of, and the impact on the environment and biodiversity. Social factors measure how a company and its business activities affect the social environment — employees, customers, suppliers, and the local community. Corporate governance refers to a company's internal supervisory system. It consists of procedures, standards, and control mechanisms implemented to ensure effective management, improve decision-making processes, comply with laws and regulations, and consider the needs of external stakeholders, including investors (GPW, 2021). Companies face constant pressure from shareholders and other stakeholder groups to perform better in social responsibility (Dorfleitner, Halbritter, & Nguyen, 2015). Therefore, ESG constantly evolves, and organisations increasingly integrate ESG factors into their operations. According to Reuters (2018), the right approach to ESG management is still somewhat undefined but should certainly include a four-step process:

- Align ESG with the company's core strategy, products/services, and operations.
- Allocate adequate resources to address relevant ESG issues.
- Managing and measuring ESG according to well-defined KPIs.
- Engage investors, customers and employees in the effort.

The literature offers increasingly more studies on various aspects of ESG disclosures. For example, Ellili (2020), Sharma et al. (2020), and Suttipun (2021) examined the scope of ESG information disclosures and confirmed its increase over the following years. However, it still remains at a low level. Furthermore, governance information constitutes the largest part of ESG disclosures, followed by social and environmental information. Hence, the issues related to the environment and the ongoing climate change require the most urgent measures. In addition, several recent

Tab. 1. Examples of ESG metrics

E	S	G
E1. GHG Emissions	S1. CEO Pay Ratio	G1. Board Diversity
E2. Emission Intensity	S2. Gender Pay Ratio	G2. Board Independence
E3. Energy Usage	S3. Employee Turnover	G3. Incentivised Pay
E4. Energy Intensity	S4. Gender Diversity	G4. Collective Bargaining
E5. Energy Mix	S5. Temporary Worker Ratio	G5. Supplier Code of Conduct
E6. Water Usage	S6. Non-Discrimination	G6. Ethics & Anti-Corruption
E7. Environmental Operations	S7. Injury Rate	G7. Data Privacy
E8. Climate Oversight/Board	S8. Global Health & Safety	G8. ESG Reporting
E9. Climate Oversight/Management	S9. Child & Forced Labour	G9. Disclosure Practices
E10. Climate Risk Mitigation	S10. Human Rights	G10. External Assurance

Source: (The Nasdaq ESG Reporting Guide, 2019, p. 13).

Tab. 2. ESG reporting initiatives

Initiative	Name	Year	Theme	Description
GRI	Global Reporting Initiative	2023	General	Sector-overarching sustainability reporting standards aiming to inform all stakeholders.
SASB	Sustainability Accounting Standards Board	2023	General	Sector-specific reporting framework focused on financial materiality and geared towards investors and capital providers.
UN SDG	United Nations Sustainable Development Goals	2015	General	A pact signed by businesses pledging to adopt sustainable business practices aligned with the Sustainable Development Goals.
IIRC	International Integrated Reporting Council	2013	General	Integrated reporting framework aiming to link traditional financial and sustainability disclosure. Recently merged with SASB in the Value Reporting Foundation.
CDP	Carbon Disclosure Project	2020	Climate	Non-profit with a focus on data collection and content for climate reporting.
CDSB	Climate Disclosure Standards Board	2010	Climate	Non-profit global environment disclosure framework geared towards investors and financial markets.
TCFD	Task Force on Climate-Related Financial Disclosures	2017	Climate	Climate-related risk disclosure focused on the financial impacts of ESG risks.
GHG Protocol	Greenhouse Gas Protocol	2001	Climate	Greenhouse gas accounting standards and comprehensive calculation guides.
SBTi	Science Based Targets Initiative	2014	Climate	Association approving emission targets in line with the Paris Agreement (a 1.5C reduction by 2030).

Source: (Nordea, 2021).

studies (Manita et al., 2018; Arayssi et al., 2020; Shakil, 2021; De Masi et al., 2021; Korzeb et al., 2024; Tancke et al., 2023; Hofbauer & Limanskis, 2022) examined the impact of various corporate governance mechanisms on ESG disclosure. This only confirms that ESG is gaining more recognition.

First, the main shortcoming of the ESG concept is the lack of universally accepted and verifiable evaluation criteria. Consequently, ESG indicators can differ significantly depending on who is setting them. Before deciding what initiatives, generally accepted frameworks and ESG standards to use, it is important to understand the difference between the two terms (Courtnell, 2022):

- ESG framework is a generally accepted framework, which is broad in scope, giving a set of principles to guide and shape an understanding of a specific topic, ESG in this case. The framework will guide the ESG reporting but will not provide a methodology for collecting information, data or reporting itself. Frameworks are useful alongside ESG standards or when there is no well-defined standard.
- ESG standards are specific by nature. They contain detailed criteria explaining what should be reported. In the ESG context, they specify how information and data are collected and how the report should be made. The standards make the framework more practical by providing comparable, consistent and reliable disclosures.

Table 2 presents a set of major reporting frameworks and ESG reporting standards together with the year of issue of the latest guidelines.

The table above shows that the market offers a myriad of climate information frameworks. The most important initiatives in this area include CDP, which has successfully standardised carbon disclosure by companies in various industries, and TCFD, which was endorsed by the EU and found its way into regulatory requirements elsewhere. On the other hand, in terms of general reporting guidelines, GRI, SASB, UN SDGs and IIRC are certainly relevant. The Global Reporting Initiative (GRI) and the Sustainability Accounting Standards Board (SASB) collaborated to harmonise disclosure frameworks. GRI was one of the first companies to introduce corporate sustainability disclosure principles. Founded in 1997, GRI provides a global, sector-independent standard for disclosing information about the impact of a company's activities on its overall stakeholders. SASB, founded in 2011, applies a financial materiality approach to sustainability disclosure, aiming to provide a more sector-specific view of the financial impact of ESG issues on a company. Geographically, while SASB has historically been more firmly anchored in the North American market, the framework is gaining traction in Europe (and Scandinavia). Cementing harmonisation, GRI and SASB issued a guide on alignment with both initiatives in April 2021 (GRI and SASB, 2021). The guidance emphasises that:

- GRI provides general guidelines for disclosure.
- SASB streamlines how reports are issued to investors and financial entities.

Further work has also begun towards harmonising guidelines for reporting sustainability issues. An initiative by five leading sustainability reporting organisations (GRI, SASB, IIRC, CDP and CDSB) aims to simplify corporate sustainability reporting by developing common market guidelines to bridge the gap between financial and sustainability reporting (Nordea, 2021).

Currently, the GRI Standards created by the Global Reporting Initiative are clearly number one in Poland and globally when it comes to standards used to prepare sustainability reports. According to the KPMG Global Survey of Sustainability Reporting 2022, 68 % of the largest global companies creating their own sustainability reports use GRI standards in this regard. The Polish market has an analogous situation: at the moment, there is no other ESG reporting standard as popular as GRI. Almost half of the surveyed companies (45 %) indicate it in their reports, and this percentage is consistently growing (Oczyp & Grzybek, 2023). With this in mind, the article focuses on a detailed analysis of the standard.

All sustainability reports prepared according to GRI and published after 1 January 2023 are subject to the new version of GRI Standards, labelled as GRI Standards 2021 as of the date of publication. GRI Standards 2021 introduce several important changes that should be kept in mind when preparing the report (Oczyp & Grzybek, 2023):

- A broader form of reporting on due diligence and human rights issues than before;
- A change in the approach to core issues and key reporting principles;
- A focus on a thorough and detailed definition of the materiality analysis process.

GRI Standards 2021 also requires adherence to eight reporting principles: information in the report should be accurate, balanced, transparent, comparable, complete, include sustainability context, be timely and verifiable.

2. Research methods

This study used the case study method on selected automotive industry companies. No simple definition of a case study exists (Heale & Twycross, 2018). Flyvbjerg emphasised that some of the definitions in the literature may be misleading and indicated five misunderstandings regarding this research method (2011). This study adopted a definition related to management science, as described by Grzegorczyk: it is a detailed description, usually of a real economic phenomenon, e.g., an organisation, a management process, its elements or the organisation's environment, to formulate conclusions about the causes and results of its course. The method is empirical, as it analyses and evaluates real phenomena. The case study is used especially for descriptive research topics. It then answers what happened, where and how (2015). Case study research is one of the most important research techniques of the grounded theory (GT), which can be adopted to produce a theory from qualitative data, fitting well with the case study research that explores complex social and psychological experiences (Fleet, Reeves, 2023). Moreover, a synergistic combination of case study research and grounded theory demonstrates a vibrant and flexible qualitative approach (Arshad, Ahlan, & Ibrahim, 2013). The grounded theory and case study have one

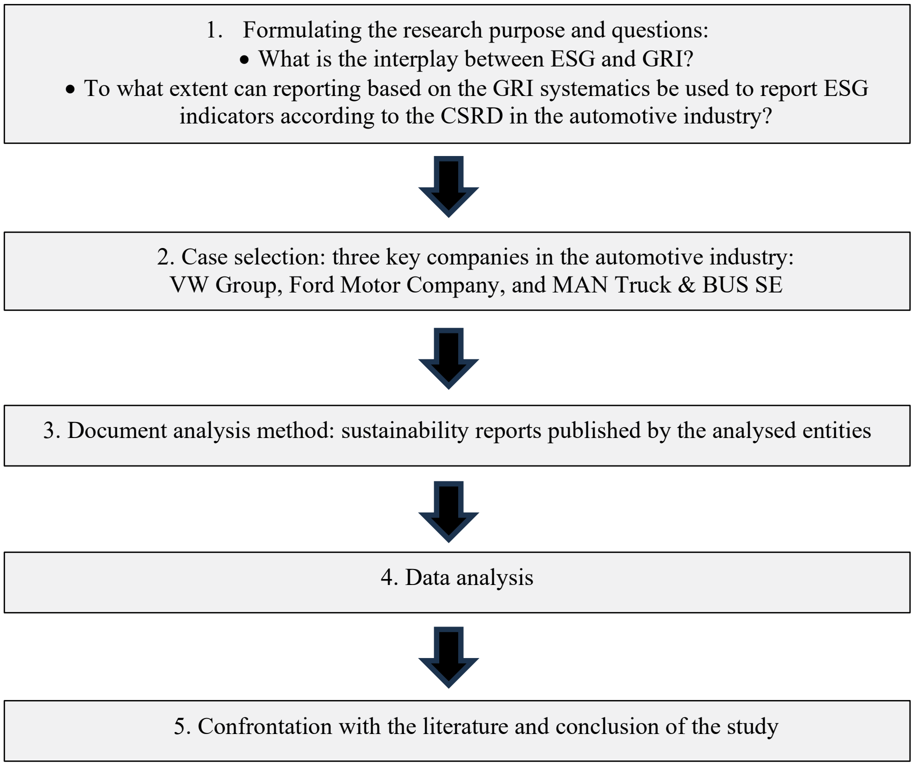

Fig. 1. Research methodology

thing in common: the general research process begins with a research problem. It proceeds to questions, data collection, data analysis and interpretations and the research report.

The study had several steps (Fig. 1): defining the research topic, formulating research questions, selecting cases and data collection tools, analysing data, reviewing the literature on the development of non-financial reporting, and considering the requirements and guidelines for reporting the effects of environmental, social and governance activities.

The selected businesses are three leading automotive companies that report on sustainability indicators. Volkswagen Group is one of the world's leading automobile manufacturers and the largest maker of commercial vehicles in Europe, with headquarters in Wolfsburg (Germany). In 2023, it delivered 9.31 million vehicles to the market worldwide (Statista, 2024). Ford Motor Company has American roots and is the world's first and oldest large-scale car manufacturer, founded in the early 20th century. MAN Truck & Bus is one of Europe's leading commercial vehicle manufacturers focused on producing trucks, buses and vans. These entities were selected using a purposive selection method, considering the diversity of their origin, size and products offered.

The next phase studied sustainability reports of analysed entities published in 2023 for 2022 or 2021. Next, three tables were made to illustrate how environmental, social and governance factors are reported based on GRI standards against the requirements of the CSRD of three automotive companies: VW Group, Ford Motor Company and MAN Truck & BUS SE based on the sustainability reports. The case study aimed to illustrate the similarities and differences in reporting sustainability indicators in relation to the same guidelines.

Then, the results were discussed, pointing out gaps between the guidelines and the reported indicators. Several recommendations were made, which led to the conclusions below.

3. Research results

Although the automotive industry is widely regarded as one of the most environmentally damag-

Tab. 3. Reporting on environmental factors

GRI Standards	GRI 301: Materials	• materials used (weight or volume) • recycled input materials used • recycled products and their packaging materials
	GRI 302: Energy	• energy consumption within the organisation • energy consumption outside the organisation • energy intensity • reduction in energy consumption • reduction in energy demand for products and services
	GRI 303: Water and sewage	• interaction with water as a shared resource • management of impacts related to water discharge • water abstraction • water discharge • water consumption
	GRI 304: Biodiversity	• operational land owned, leased, protected areas, and areas of high biodiversity value outside protected areas • significant impact of activities, products and services on biodiversity • habitats protected or restored • IUCN Red List species and National Conservation List species with habitats in areas covered by activities
	GRI 305: Emissions	• direct (Scope 1) • indirect (Scope 2) • other indirect greenhouse gas emissions (Scope 3) • emission intensity • reduction of greenhouse gas emissions • emissions of ozone-depleting substances • nitrogen oxides (NOx), sulphur oxides (SOx) and other significant air emissions
	GRI 306: Waste	• water discharge by quality and destination • waste by type and disposal method • significant spills • transportation of hazardous waste • water bodies affected by water discharges and/or runoffs
	GRI 308: Supplier's environmental assessment	• new suppliers screened using environmental criteria • negative environmental impacts in the supply chain and actions taken
CSRD Directive	• Climate change — mitigation and adaptation • Water and marine resources • Resource utilisation and the circular economy • Pollution • Biodiversity and ecosystems	
VW Group	DECARBONISATION KPIs decarbonisation: • decarbonisation index (strategic indicator) • average passenger car emissions (strategic indicator) by the US and the EU • number of cars produced with alternative propulsion technologies (gas, hybrid, and electric) • product carbon footprint • greenhouse gas emissions (Scope 1, 2, and 3) Environmental management KPIs (for all brands and separately for passenger car and commercial vehicle production): • specific emission reduction (strategic indicator) • emissions of volatile organic compounds Direct NOx- and SO2-emissions (for all brands and separately for passenger car and commercial vehicle production): • nitrogen oxides • sulphur dioxide CIRCULAR ECONOMY KPIs circular economy: • avoidance of CO2 emissions through the aluminium closed-loop project from 2017 • percentage of freshwater demand in locations in vulnerable areas KPIs environmental management: • number of locations certified according to ISO 14001 or EMAS at Volkswagen Group/ VW AG Company • number of production sites certified according to ISO 50001 in the Volkswagen Group Energy consumption (overall and per car; for all brands and separately for passenger car and commercial vehicle production):	

	• electricity • heat • fuel gases for production processes • water • sewage • waste (non-hazardous, hazardous and metallic) for recycling • waste for disposal (non-hazardous and hazardous) • chemical oxygen demand • water intake (divided into sources: ground, surface, and externally sourced) • wastewater discharge (water reservoirs, municipal wastewater treatment plants) • number of countermeasures implemented (in the Maßnahmen@Web system)
Ford Motor Company	Vehicle fuel consumption and CO2 emissions • Ford Corporation's average fuel consumption in the US • CO2 emissions of Ford vehicles in the US, Europe, Switzerland and China on a per-vehicle basis (broken down into passenger cars and commercial vehicles) • average fuel consumption of Ford Corporation in China • CO2 emissions of Ford corporate vehicles in China per vehicle (broken down by passenger cars and commercial vehicles) Vehicle emissions other than CO2 • Ford's average NOx and NMOG emissions in the US Operational energy consumption and CO2 emissions • worldwide facility energy consumption (indirect and direct; broken down into renewable and non-renewable electricity from 2021) • worldwide greenhouse gas emissions from facilities • greenhouse gas emissions from worldwide operations CO2 emissions of purchased goods and services • indirect emissions (purchased goods and services; for 2021 only) Emissions (VOCs and others) • volatile organic compounds released by production facilities • emissions reported to the Toxics Release Inventory (TRI) in the US (absolute and per-vehicle values) • emissions reported to the National Pollutant Release Inventory (NPRI) in Canada (absolute and per-vehicle values) Waste • regional waste sent to landfill (absolute value) by region and per vehicle • regional hazardous waste (absolute value) by region and per vehicle • hazardous waste by the method of disposal (absolute value) • non-hazardous waste by disposal method (absolute value) • total waste by disposal method (absolute value) • metal scrap (absolute value by region) • total waste volume and percentage recycled Water • global water consumption per vehicle produced • global water consumption by source • water consumption by region • reuse from local wastewater treatment plant • discharge of process wastewater
MAN Truck and BUS SE	DECARBONISATION • GHG emissions across the value chain: Scope 1, 2, and 3 and other indirect emissions — absolute emissions and relative to the base year 2019 • energy consumption in production processes • direct energy consumption (combustion fuels and gases) and indirect energy consumption, including: - electricity — total consumption and share of energy from renewable energy sources - thermal energy — total consumption and share of self-generated energy from renewable energy sources and share of purchased energy from renewable energy sources • direct primary energy consumption (fuel oil, natural gas, diesel, and other) • energy consumption per vehicle • absolute indirect and direct CO2 emissions • CO2 emissions per vehicle • atmospheric pollutants (sulphur dioxide, nitrogen oxides, particulate matter, and volatile organic compounds) • logistics-related CO2 emissions per vehicle produced (in 2016–2021) CIRCULAR ECONOMY • production waste (broken down into hazardous and non-hazardous, and into disposal and recovery) • metal waste • recycling rate • water consumption (total, from external sources, and abstracted by the company for its own use, including well water) • surface water consumption • reused water

	• used rainwater • wastewater RESPONSIBLE TRANSPORT AND MOBILITY SOLUTIONS • number of connected vehicles[1] • number of electric cars (orders and sales broken down by trucks, commercial vehicles, and buses) — for 2021 only

Source: Elaborated by the author based on (Directive (EU) 2022/2464 of the European Parliament and of the Council; Consolidated Set of the GRI Standards; ESG Kennzahlen Volkswagen AG; ESG Overview Ford Motor Company; Sustainability Report 2021 Man Truck and BUS).

Tab. 4. Reporting on social factors

GRI Standards	GRI 401: Employment	• hiring new employees and employee turnover • benefits offered to full-time employees that are not offered to temporary or part-time employees • parental leave
	GRI 402: Labour relations	• minimum notice periods for operational changes
	GRI 403: Health and safety in the workplace	• health and safety management system and management of impacts related to water discharge • hazard identification, risk assessment and incident investigation • occupational health service • worker participation, consultation and communication on occupational health and safety • training of employees in occupational health and safety • employee health promotion • prevention and mitigation of occupational health and safety impacts directly related to business relationships • employees covered by the occupational safety and health management system • work-related injuries • work-related illness
	GRI 404: Training and education	• average number of training hours per year per employee • employee upskilling programmes and transition assistance • percentage of employees receiving regular performance and career development reviews
	GRI 405: Diversity and equal opportunities	• diversity of supervisors and employees • the ratio of base salary and women's pay to men's
	GRI 406: Indiscretion	• cases of discrimination and corrective actions taken
	GRI 407: Freedom of association and collective bargaining	• operations and suppliers where the right to freedom of association and collective bargaining may be threatened
	GRI 408: Child labour	• operations and suppliers at significant risk of child labour incidents
	GRI 409: Forced labour and modern slavery	• establishments and suppliers at significant risk of incidents of forced labour
	GRI 410: Security practices	• security personnel trained in human rights policies or procedures
	GRI 411: Rights of indigenous peoples	• violations of indigenous peoples' rights
	GRI 413: Local communities	• operations with community participation, impact assessment and development programmes • operations with significant actual and potential negative impacts on local communities
	GRI 414: Social evaluation of the supplier	• new suppliers screened using social criteria • negative social impacts in the supply chain and actions taken

[1] Digital connectivity and data exchange are important prerequisites for improving efficiency and safety in the transportation sector and significantly reducing CO2 emissions by controlling entire systems (MAN, 2022).

	GRI 415 Public policy	• political contributions
	GRI 416: Health and safety of customers	• assessment of the impact of products and services on health and safety of service categories • cases of non-compliance regarding the impact of products and services on health and safety
	GRI 417: Marketing and signage	• requirements for information on products and services and their labelling • incidents of non-compliance regarding product and service information and labelling • incidents of non-compliance regarding marketing communications
	GRI 418: Customer privacy	• legitimate complaints about violations of customer privacy and loss of customer data
CSRD Directive	• equal treatment and equal opportunities for all (equal pay, development opportunities, integration of excluded persons, and prevention of violence) • working and employment conditions (working time, freedom of association, workers' right to information and consultation, safety and hygiene at work) • respect for human rights (fundamental freedoms, democratic principles and norms as established in the International Bill of Human Rights and other fundamental UN conventions)	
VW Group	PEOPLE IN TRANSFORMATION • number of countries where the Volkswagen Group operates • number of production plants • number of Volkswagen Group employees broken down by concern and type of contract • age structure of Volkswagen Group employees • fluctuation by gender • number of trainees • share of women in the total number of employees, in management positions and in trainee positions • result of the sentiment barometer: share, satisfaction index, and employer attractiveness • employee suggestion system • attractiveness of the employer in the environment • professional development of employees • preventive health care and occupational safety • accident rate indexes DIVERSITY • participation of women in management • internationalisation in TOP executives • diversity index • number of dismissals for discrimination violations	
Ford Motor Company	DIVERSITY • number and percentage distribution of salaried employees by gender • composition of the Board of Directors — percentage share of individual genders and minorities • composition of senior management — percentage share of individual genders and minorities • share of women in senior management by region and business unit • share of women in middle management by region and business unit • share of women in supervisory positions by regions and business units • board demographics (number of members by gender and minorities for 2020 and 2021 only) • executive demographics (number of members by gender and minorities for 2020 and 2021 only) • ethnic data on the US workforce (percentage of each race in the total workforce) • share of women in the total number of employees in the US (for 2020 and 2021 only) HEALTH AND SAFETY • the global rate of incidents leading to lost work time (per 100 employees) • rate of incidents leading to lost work time (per 100 employees) by region • the global number of fatalities EMPLOYEE ENGAGEMENT • percentage rate of voluntary resignations in major markets • number of confirmed harassment allegations by region (for 2021 only) DIVERSITY OF SUPPLIERS • total dollar volume of purchases (within the US) from companies owned by minorities, veterans, women, and small businesses	
MAN Truck and BUS SE	PEOPLE AND CULTURE • number of employees in total and by business area • employee structure (permanent employees, temporary employees, apprentices, passive partial retirement by gender in each case and employees before subcontractors) • number of employees (broken down by Germany and other countries) • age structure of employees	

	• costs incurred for training and education • women in management positions (number and % share) • number of accidents causing downtime, accident-incident index, accident severity index • donations SAFETY ON ROADS, PRODUCTS, AND SERVICES No indicators, the report describes ongoing projects to ensure the safety of its products for drivers and road users.

Source: Elaborated by the author based on (Directive (EU) 2022/2464 of the European Parliament and the Council; Consolidated Set of the GRI Standards; ESG Kennzahlen Volkswagen AG; ESG Overview Ford Motor Company; Sustainability Report 2021 Man Truck and BUS).

Tab. 5. Reporting on corporate governance factors

GRI Standards	GRI 201: Corporate governance factors	• direct economic value generated and distributed • financial effects and other risks and opportunities arising from climate change • liabilities for defined benefit plans and other pension plans • financial assistance received from the government
	GRI 202: Market presence	• ratio of standard starting wage by gender to local minimum wage • percentage of senior executives hired from the local community
	GRI 203: Indirect impact on the economy	• investment in infrastructure and supported services • significant indirect economic impacts
	GRI 204: Procurement practices	• percentage of spending on local suppliers
	GRI 205: Countering corruption	• operations assessed for corruption risks • communication and training on anti-corruption policies and procedures • confirmed cases of corruption and actions taken
	GRI 206: Anti-competitive behaviour	• legal actions on anti-concern behaviour • antitrust and monopoly practices
	GRI 207: Taxes	• tax governance, control and risk management • stakeholder engagement and management of tax concerns
CSRD Directive	• the role, composition and expertise of the entity's administrative, management and supervisory bodies with respect to sustainability issues • internal control and risk management systems used by the entity • business ethics and corporate culture (anti-bribery and corruption, animal welfare) • the entity's activities and commitments related to political influence (including lobbying) • management and quality of relations with customers, suppliers and communities affected by the entity's activities (including payment practices)	
VW Group	LEGACY • Together For Integrity programme • Infopoint • Code of Conduct • anti-corruption • reported violations • Business Partner Due Diligence audits • Management culture (keeping the rules, error culture, and righteous behaviour) RESPONSIBILITY FOR SUPPLY CHAINS AND THE ECONOMY • number of direct suppliers of the Volkswagen Group • number of countries where the Volkswagen Group has direct suppliers • number of sustainable purchasing network experts • number of suppliers with completed SAQ (self-assessment questionnaire) • improvements at suppliers based on SAQ (self-assessment questionnaire) • number of production facilities for which a human rights risk assessment has been conducted • suppliers with a certified environmental management system according to ISO 14001 and/or EMAS • buyers who have participated in qualification activities on sustainability • suppliers who have received sustainability training • average violations of sustainability requirements by region • due diligence inspections of business partners • suppliers who have completed an e-learning module on sustainability	

	• available supplier ratios • complaint mechanism cases (by region; by topic: social, compliance, environment, and cross-cutting topics) • termination of cooperation with suppliers • complaint mechanism cases: direct supplier • list of countries identified as countries with higher human rights risks (TOP 15)
Ford Motor Company	PRODUCT SAFETY • Ford and Lincoln nameplates with an overall rating of five stars in US NCAP and European NCAP (for 2020 and 2021 only) • number of safety recalls (US market) • number of recalled passenger cars in the US SUPPLY CHAIN MANAGEMENT • number of working conditions assessments completed by the end of 2021 by region • number of supplementary working conditions assessments completed by the end of 2021 by region • number of audits performed at suppliers (for 2021 only) • results of supplier audits – number of nonconformities in initial audits in 2021, by category: management systems, employees, health and safety, environment and ethics, and detailed subcategories (for 2021 only) • supplier audit results – Initial and final (average value)
MAN Truck and BUS SE	COMPLIANCE, ETHICS AND INTEGRITY • compliance indicators (for 2021): • a tool for validating business partners • compliance training • compliance helpdesk • Together4Integrity • additional indicators ACCOUNTABILITY IN THE VALUE CHAIN No indicators, the report describes various initiatives to improve sustainability performance across the value chain

Source: Elaborated by the author based on (Directive (EU) 2022/2464 of the European Parliament and the Council; Consolidated Set of the GRI Standards; ESG Kennzahlen Volkswagen AG; ESG Overview Ford Motor Company; Sustainability Report 2021 Man Truck and BUS).

ing, according to the Capgemini report, the automotive sector is currently ahead of other industries in meeting global sustainability standards. However, only 9 % of the 500 analysed automotive companies can be classified as high-performing "sustainability leaders", as 91 % of them have not yet reached sustainability maturity (Capgemini, 2020). This means a very high potential for development in this area. The following tables illustrate how environmental, social and governance factors of the three automotive companies (VW Group, Ford Motor Company, and MAN Truck & BUS SE) are reported based on GRI standards against the requirements of the CSRD based on sustainability reports.

3.1. Environmental factors

Environmental factors (Table 3) are the most extensive group of indicators reported under ESG in the analysed companies.

The main environmental reporting points of the automotive companies analysed above include energy consumption, water consumption, the amount of wastewater generated, CO2 emissions, greenhouse gas emissions, and the amount of waste generated. None of the above companies address the issue of materials used in production processes (a GRI item) or biodiversity (a GRI item and a CSRD requirement) in their reports. The environmental assessment of suppliers is included by Volkswagen and Ford corporations in the Corporate Governance section and is not part of the reporting of environmental indicators. In addition, a number of indicators presented by the companies go beyond those proposed by GRI or the CSRD requirements. Examples of such indicators include issues related to certification of environmental management systems (Volkswagen), alternative drives (Volkswagen, MAN), corporate fuel consumption (Ford), or recycling rates (MAN).

3.2. Social factors

Social factors illustrate the relationships linking the company with its employees and other groups, such as local communities, contractors or customers (Table 4).

The main points of social reporting by the automotive companies analysed above include employee numbers, structures and turnover, type of contract, preventive health care, occupational safety (including accidents and incidents), diversity, discrimination and bullying, and training and education. None of the above companies address the issues of social evaluation of suppliers, freedom of association, marketing and labelling, or child labour (GRI) in their reports. In addition, several indicators presented by the above companies that go beyond those proposed by GRI or CSRD. Examples of such indicators are issues related to the mood barometer, the employee suggestion system, the attractiveness of the employer in the environment (Volkswagen), the volume of purchases from companies owned by veterans, women, small businesses (Ford), or donations (MAN).

3.3. Corporate governance factors

Factors regarding corporate governance in the analysed companies are depicted in the table below (Table 5).

The main reporting points of the corporate governance of automotive companies include integrity, ethics and honesty, supply chain management and product safety. None of the companies address economic, local community or tax (GRI) indicators in their reports. An example of indicators beyond those indicated in the table above are issues related to product safety (Ford).

Discussion

The surveyed corporations report largely on the indicators contained in the GRI standards or the CSRD, but not all of them are included in their sustainability reports. These embrace reporting on materials used in production processes (a GRI element), biodiversity indicators (a GRI element and a CSRD requirement), social assessment of suppliers, freedom of association, marketing and labelling, or child labour (GRI), and economic, community or tax indicators (GRI).

On the other hand, the surveyed companies report on indicators that go beyond the GRI guidelines and the CSRD. In the area of the environment, these include issues related to the certification of environmental management systems (Volkswagen), alternative drives (Volkswagen, MAN), the corporation's fuel consumption (Ford), or the recycling rate (MAN). In the area of social indicators, the corporations additionally report issues related to the mood barometer, employee suggestion system, the attractiveness of the employer in the environment (Volkswagen), the volume of purchases from companies owned by veterans, women and small businesses (Ford), and donations (MAN). In corporate governance, one company additionally reports on product safety issues (Ford).

The described deviations may be the result of a mismatch between the universal CRSD and GRI guidelines and the specific characteristics of the automotive industry. The Global Sustainability Standards Board, which is responsible for the GRI guidelines, is working on sector-specific recommendations for 40 sectors, starting with those with the greatest sustainability impacts, which have not yet been officially developed for the automotive industry (GSSB, 2021). The GRI sector standards should consider current challenges and trends in the related industry, e.g., the electrification of drives or the development towards autonomous driving, which raises a number of legal and ethical issues that need to be addressed. To facilitate and, at the same time, standardise the reporting of ESG indicators, corporations under study can use the piloted but not yet approved version of the GRI Automotive Sector Supplement (Chamberlain, 2013).

The analysed sustainability reports cover the year 2022, and thus, they do not consider the European Sustainability Reporting Standards (ESRS) published in December 2023 (arising from the CSRD). It will only be possible to test for their application once the 2024 reports have been published. The currently published ESRS are dedicated to all industries, and the development of sectoral ESRS was scheduled in the European Commission's work programme for 2024, although recent reports herald a postponement of two years (ESGinfo.pl, 2023).

Conclusions

The research analysed reports of sustainability-related activities presented by three major automotive corporations. Based on the study, the main difficulty in reporting non-financial indicators is the lack of uniform guidelines on how to calculate metrics and their scope, which leads to different interpretations of existing guidelines. As a result, the lack of clarity in the data poses problems for comparison over time and between different organisations.

The European Union, recognising that no existing standards or frameworks on their own meet the Union's sustainability reporting needs and following the publication of the CSRD had been working on the development of mandatory European Sustainability Reporting Standards (ESRS), which were published in December 2023.

The results of the analysis allow for the formulation of the following conclusions: GRI represents a practical translation of ESG concepts to the operational level, directly applicable to companies regardless of their size. In addition, published sector standards for selected industries (currently, still absent for the automotive industry) enable consistent and complete reporting regarding the sustainability impact of individual sectors; So far, the indicators reported by the analysed companies provide a good starting point for reporting ESG indicators according to the CSRD, although a definitive assessment will not be possible until one year after the publication of the ESRS.

The surveyed companies report environmental indicators to the widest extent, confirming findings from the literature study, indicating that the market offers a myriad of climate information frameworks. This is related to the numerous environmental requirements placed on the automotive industry, which vehicle manufacturers have had to meet for years. However, the indicators refer to different time periods and are presented in a variety of units and for different business units, which makes it impossible to compare them directly, despite the fact that all the analysed companies are from the same industry. On the other hand, past practices in reporting sustainability activities may be helpful in developing reporting systematics in line with the ESG concept. The indicators identified by the automotive corporations as "ESG indicators" are often rooted in already implemented management systems, which is the first step to meeting the CSRD requirements.

ESG topics are also reflected in corporate strategies, which indicates the high priority placed on the issue, and existing reporting practices can be helpful in developing reporting systematics in line with the ESG concept. The research shows that the automotive industry is partially ready to report on sustainability indicators, and the time pressure associated with the introduction of mandatory reporting will increase work in this area.

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Life cycle perspective in design and product development

Katarzyna Joachimiak-Lechman

ABSTRACT
Eco-design is one of the cornerstones of the modern economy, as reflected in the policies aimed at implementing the principles of design for the environment in the European Union legislation. A life cycle perspective is a feature of eco-design. The study aimed to determine whether and to what extent the selected companies operating in manufacturing sectors consider life cycle perspectives when designing and developing the products they offer. The main research area discussed in the following article focused on the question: What kind of activities related to the idea of life cycle thinking in product policy can be identified in the analysed enterprises? Qualitative research was conducted using the individual in-depth interview method with representatives of selected industries located in Poland. Eight manufacturer groups were invited to participate in the study. Based on the recruitment process, 24 companies were chosen for the interview. Individual in-depth interviews were conducted using Microsoft Teams, following the ICC/ESOMAR Code 2016 standards. Based on the results, most companies that participated in the study considered the life cycle perspective when designing or further developing products. However, their activities varied in scope. The activities of the ten interviewed companies could be regarded as advanced. For six companies, the advanced activities targeted the product's use phase. Two companies undertook such activities at more than one life cycle stage. The study provides evidence that the surveyed companies are beginning to think beyond operational boundaries and changing their pro-environmental orientation, albeit unimpressively. The paper provides evidence that eco-design requirements are an unquestionable driver for activities from a life cycle perspective. All surveyed manufacturers of energy-powered products are taking measures to reduce energy intensity with less activity, for example, ensuring the durability/reliability of products and finding solutions to facilitate disassembly and recycling.

KEY WORDS
life cycle thinking, eco-design, product development, Sustainable Products Initiative, sustainability, European Green Deal, EGD

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Introduction

The Corporate Sustainability Reporting Directive (CSRD) and the European Sustainability Reporting Standards (ESRS) highlight the growing importance of the circular economy (CE) in the business context. According to the EU Taxonomy (Regulation (EU) 2020/852), one of the environmental goals is the transformation towards CE. The core ESRS standards include two cross-cutting and ten thematic standards. One of them specifically focuses on resource use and circular economy (ESRS E5), where it was emphasised

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that eco-design contributes to optimising resource consumption in the whole life cycle (Commission Delegated Regulation (EU) 2023/2772). Thinking with a life cycle perspective has been gaining importance for a long time. In 2022, the European Commission prepared a proposal for a regulation on eco-design for sustainable products. It is planned to broaden the scope of the existing eco-design directive (2009/125/EC) in terms of products and requirements. The new regulations should go beyond energy-powered products and cover the broadest possible range of products to support the transition to a circular economy. A new Circular Economy Action Plan sets priorities for the Sustainable Products Initiative and recognises electronics, information and communications technologies, textiles, furniture, and products used in the construction sector (e.g., chemicals) as relevant in this context (COM(2020)98). Considering the above facts, eco-design can be expected to become more popular in practice. The issue of eco-design emerged in the early 1970s. Over the past decades, several initiatives developed this concept and gathered practical experience.

Several factors impact the environmental performance of products in the life cycle. These include durability, reliability, ease of repair and maintenance, ease of upgrading, reusability, remanufacturing, refurbishment, quality of recycling, and energy and resource efficiency (COM(2022)142). The implementation of products based on life cycle thinking concepts is a challenge. This is due to competence gaps or other organisational barriers and the specific problems faced by organisations, especially small and medium-sized enterprises (SMEs) (Witczak et al., 2014; Selech et al., 2014). Nevertheless, given the European Union's intensive efforts on sustainable products, it is expected that in the near future, companies will face the need to identify and assess the environmental aspects of their products more extensively and act in this regard. This article evaluates the status quo in this area. Although some papers investigate the product-oriented pro-environmental practices (e.g., Triguero et al., 2023; Dostatni et al., 2023; Siwiec et al., 2024), the range of actions applied by companies from different industries to reduce the impact of the product life cycle has not been studied in depth.

This research mainly aimed to determine whether and to what extent Polish producers of selected industries consider a life cycle perspective when designing or developing their products. To achieve the primary objective of the study, qualitative research was conducted using the individual in-depth interview method (Glinka & Czakon, 2021). During the interview, activities implemented by selected companies related to the idea of life cycle thinking were identified. The qualitative research allowed for deepening the knowledge of practical solutions and presenting an expanded catalogue of activities occurring at different life cycle stages. The respondents' free statements also made it possible to identify their general attitudes, opinions, and their customers' preferences for eco-design.

Eight groups of producers were invited to the study, with the following Polish Classification of Activities (PKD code): 14.13, 31.09, 26.20, 27.40, 27.51, 23.32, 23.99, and 20.30. The above industries were selected considering the European Union's Sustainable Products Initiative. Based on the recruitment process, 24 companies were selected to participate in the study (three producers for each selected industry). Employees with managerial positions responsible for the company's product policy participated in the survey.

The remaining paper is structured as follows. First, the theoretical and practical aspects of eco-design are briefly described. Then, the selected results of research illustrating the implementation of eco-design in enterprises are presented. Next, the research methodology is explained, and the main findings of the research are analysed. This part presents surveyed companies' actions in product policy regarding life cycle thinking. The questions focused on the various stages of the life cycle: procurement (acquisition of production materials), production, distribution, use and final disposal. In the final sections of the paper, a discussion is held, and conclusions are drawn. It was concluded that the surveyed companies are beginning to think beyond operational boundaries and changing their pro-environmental orientation, albeit unimpressively.

1. Literature review

Eco-design has various definitions. A report compiled by the European Network of Eco-design Centres (ENEC) provides 34 definitions of the term, encompassing strategic and operational aspects. According to Lindahl and Ekermann (2013), eco-design is not a specific method or tool but rather a way of better design through analysing and synthesising to reduce environmental impacts throughout the product's life cycle (Prendeville et al., 2014, p.5). Another definition states that eco-design involves simultaneously considering the environmental impacts associated with the selection of materials, the manufacturing process, the storage and transportation phase, usage, and final disposal (Plouffe et al., 2011). According to the ISO standard, eco-design is a systematic approach that considers environmental aspects in design and development to reduce adverse environmental impacts throughout the life cycle of a product (ISO 14006:2020). Regardless of the definition, eco-design principles include many environmental issues that should be considered: avoiding toxic substances, using materials with recycled content, reducing the energy and resource intensity of the production process, minimising energy and resource consumption at the use stage of products, promoting repairability, expansion, upgrading, and extending the life of products, facilitating disassembly and recycling, etc. (Luttropp & Lagerstedt, 2006).

The greatest challenge in designing sustainable products is the selection of appropriate design strategies based on life cycle thinking (Bakker et al., 2014). Life cycle thinking means that when designing or developing a product, a company needs to consider which environmental aspect of a product is a critical point in the life cycle and implement appropriate measures for that area, even if that point is outside the "company's gate". Numerous environmental classifications of products can be found in the literature, offering insights into crucial environmental hotspots in the product life cycle (Joachimiak-Lechman et al., 2017; Joachimiak-Lechman et al., 2019). In general, a distinction is made between production-intensive, transportation-intensive, use-intensive, and disposal-intensive products.

Many papers present practical aspects of eco-design. From recent reports, it is worth mentioning the new eco-design model based on a life cycle integrated framework (Kong et al., 2022), the proposition to use Cuckoo search and life cycle assessment to support design decision-making (Ng & Tang, 2022), and the impacts of Industry 4.0 technologies on materials, products, and processes in the context of eco-design (Keivanpour, 2022). Li et al. (2024) established an eco-design performance evaluation system. A linked two-stage network Data Envelopment Analysis (DEA) model was developed, which includes Internal and Supplier Management (ISM) and Openness and Collaboration (OC). The new concept is also Eco-Design for Additive Manufacturing (EcoDfAM) using the Web Ontology Language (OWL) to model the Sustainable Design Knowledge (SDK) (Wang et al., 2024). Favi et al. (2019) described the implementation of a novel eco-design teaching approach involving the company's employees from different technical departments.

The literature also discusses the eco-design implementation in enterprises. The study presented by Dekoninck et al. (2016) addressed the problem of the slow take-up of eco-design in industry. Case studies from nine manufacturing companies from five different countries were reported based on interviews with key eco-design personnel. Challenges were identified in five areas: strategy, tools, collaboration, management and knowledge. The management category of challenges was the most frequently mentioned by the sampled companies (Dekoninck et al., 2016). Based on 61 interviews with automobile company suppliers, the interest businesses take in eco-design depends on supply chain management. It was proved that the perception of eco-design is very strong among the electric and electronic part suppliers. The perception of eco-design among other suppliers is weak (Akman et al., 2021). Another important issue is the company's level of eco-innovation. Interviews conducted with ten companies in Slovenia that actively adopt and develop eco-innovations proved that the analysed entities implement practices of the circular economy, such as open-circle recycling, recycling and reuse of materials, rental and remote monitoring of their products, and closed resource loops (e.g., materials and water) (Hojnik et al., 2023). The survey of managers from a sample of 300 manufacturing companies in Spain showed that for product design, the most frequent practice was the design for recycling, followed by the design for reuse (DfR) and the design for disassembly (DfD) (Triguero et al., 2023).

The study investigating the adoption of green supply chain management in developing countries proved that eco-design and green marketing coupled with eco-innovation assisted in enhancing environmental image. Hence, the active involvement of organisations in innovation processes and the implementation of green management practices drive success (Bashar et al., 2023). Research efforts in Poland on the implementation of sustainable development patterns (e.g., Sikorska et al., 2005; Anuszewska et al., 2011a; Anuszewska et al., 2011b; Zuzek & Mickiewicz, 2014; Suzuki & Gemba, 2022; Słupik, 2014; Kubicka & Kupczyk, 2016) have not addressed eco-design. The most extensive report resulted from a qualitative study commissioned by the Polish

Agency for Enterprise Development, published in 2011. It was noted that few of the analysed companies had declared eco-design practices (Annuszewska et al., 2011b). Considering that many eco-design stimulants have emerged since then, eco-design can be expected to become more popular in practice. However, it seems that most SMEs are still reluctant to adopt eco-design initiatives. SMEs need to adapt to the economic model and have appropriate knowledge of production and management processes and their relationship with product innovation and the environment (Siwiec et al., 2024 cit. per Ali et al., 2021). Other analyses also confirmed the vital role of the owner and the internal corporate organisation and the barriers faced by SMEs in acquiring the necessary knowledge, thus making internal training of existing resources a key factor for them (Rodríguez-Rebès et al., 2024).

In 2023, a survey was conducted on the qualitative environmental aspects of product improvement in SMEs from the Visegrad Group countries (Czech Republic, Poland, Hungary, and Slovakia). A research sample consisted of 379 companies from the electrical machinery industry. The analysed companies focused their activities on improving products to improve their quality rather than limiting their negative environmental impact (Siwiec et al., 2024). According to the study, the most frequently used measures of environmental activity in SMEs from the V4 countries are waste generated per unit of finished product, the percentage of recycled waste, efficiency in the use of materials and energy, environmental failures (e.g., exceeding the established pollution limits and unplanned releases) and the number of incidents (Siwiec et al., 2024). Important conclusions illustrating the approach of companies to product-oriented environmental aspects also emerge from a study conducted by researchers from the Poznan University of Technology. The study focused on different manufacturing companies operating in the Greater Poland Voivodship. The main objective was to compare the involvement of manufacturing companies in environmental activity at various stages of the product life cycle. It was observed that large companies applied numerous pro-environmental solutions and continuously improved their processes. It was also concluded that in the context of SMEs, many areas require improvements; however, the willingness of SMEs to develop their environmental activities was also demonstrated (Dostatni et al., 2023).

2. Research methods

As mentioned, qualitative research was conducted using the individual in-depth interview method with representatives of selected manufacturers located in Poland (PKD codes:14.13, 31.09, 26.20, 27.40, 27.51, 23.32, 23.99, 20.30). The choice of industries was dictated by the EU initiative on sustainable products. In the clothing and furniture industry, the survey included representatives of the most numerous manufacturer groups (according to the Polish Statistical Information Centre https://bip.stat.gov.pl/dzialalnosc-statystyki-publicznej) belonging to the class "Manufacture of other outerwear" and "Manufacture of other furniture". In the electronics and electrical engineering industry, interviews were conducted with representatives of the most numerous classes ("Manufacture of computers and peripheral equipment" and "Manufacture of electric lighting equipment") and producers of household appliances, which had a significant production increase in 2020. The construction industry is the most diverse manufacturer group that belongs to different classes of the Polish Classification of Activities; thus, the qualitative study included representatives of manufacturers with a significant production increase in 2020 (more than 10 %), i.e., building ceramics, insulation materials and paints and varnishes.

Purposive sampling was used in the study. The sample selection criteria were based on production activities in selected industries and involvement in product-oriented pro-environmental initiatives. Recruitment was made using databases provided by Dan & Bradstreet (https://www.dnb.com) and the Central Economic Information Service. Dun & Bradstreet supplies a reputable company database that collects and provides comprehensive information on companies in various industries and regions. It ensures that the list of companies is comprehensive and covers a variety of companies, which allows for a reliable sample for qualitative research.

In the first stage of selection, 50 companies were recruited for the study according to the indicated PKD code. In the next stage, a trained recruiter contacted the enterprises, asking whether the company takes any pro-environmental initiatives related to the products they offer (the word "eco-design" was deliberately avoided so that companies would not assume in advance that they were not active in this area). In the case of a positive answer, the recruiter asked to

Tab. 1. Number of companies invited to participate in the study

Industry	Number of companies
Manufacture of other outerwear (PKD code:14.13)	3
Manufacture of other furniture (PKD code: 31.09)	3
Manufacture of computers and peripheral equipment (PKD code: 26.20)	3
Manufacture of electric lighting equipment (PKD code: 27.40)	3
Manufacture of household appliances (PKD code: 27.51)	3
Manufacture of building ceramics (PKD code: 23.32)	3
Production of insulating materials (PKD code:23.99)	3
Production of paints and varnishes (PKD code:20.30)	3

contact the appropriate employee, noting that a person with a managerial position responsible for product policy should participate in the interview. Recruitment was carried out until interviews were successfully arranged with representatives of companies in a given industry (three producers for each selected industry). Finally, 24 companies were selected (Table 1). The most common reason for disqualifying a company was the lack of contact (e.g., an inactive number) or refusal (due to the lack of time/the lack of willingness to participate in the interview or a declared lack of interest in the environmental aspects of the offered products).

The study was attended by nine production managers, five product managers, five owners, four environmental specialists, and one ESG coordinator. Almost half of the surveyed businesses were limited liability companies. Most of the surveyed companies (18) belonged to the SME sector, with the largest group being small entities (13). Four companies had foreign capital. Eight of the surveyed companies had formalised management systems, usually a quality management system based on ISO 9001 (as a standalone system or in integration with other management systems ISO 14001 and ISO 45001).

Individual in-depth interviews were conducted following the standards set by the ICC/ESOMAR Code 2016, using Microsoft Teams. The individual in-depth interview was based on a structured interview scenario. The interview was prepared following an in-depth review of the eco-design requirements for the analysed products included in EU Commission Regulations (EU Commission Regulations: 666/2013, 66/2014, 2019/424, 2019/2019, 2019/2020, 2019/2021, 2019/2022, 2019/2023, 305/2011, EC Regulation 1907/2006, EU Commission Decision of May 28, 2014) and proposals presented in publications of various institutions (European Environmental Bureau 2017, Nordic Council of Ministers 2018, Public Waste Agency of Flanders 2021, Environmental Coalition on Standards 2021).

Interviews were recorded, and a transcription of the content was made. The interview transcriptions went through content analysis using a predefined set of categories. The first step in the content analysis was coding. This procedure involves generating categories (codes) that conceptually cover the area under study, assigning properties to them, and linking them together to look for relationships (Glinska-Neweś & Escher, 2018). A code, therefore, in qualitative data analysis is a designation or label assigned to units of text, and it is assumed that these units can include individual sentences, statements, or sequences of statements (Kowalik & Baranowska-Prokop, 2013). The set of obtained categories was supplemented based on statements that emerged in the interviews. Finally, they were divided into smaller units, so-called subcategories. The coding of the interview resulted in a set of 268 citations. The analysis of the results of individual in-depth interviews is presented below.

3. Research results

3.1. Supply

The most important part of the study dealt with product design and development actions by the surveyed companies and focused on the various stages of the life cycle. The first question concerned the material supply process. Three areas of activities in supply were identified from analysed responses (Table 2):

- purchasing eco-friendly production materials (29 statements),

Tab. 2. Actions in the field of supply

Industry	Major category	Frequency of occurrence	Subcategory	Frequency of occurrence
Manufacture of other outerwear	We buy eco-friendly production materials	5	Fibers with content of raw materials of natural origin	2
			Fabric with content of natural dyes	2
			Fabric produced with the use of organic methods	1
Manufacture of other furniture	We buy eco-friendly production materials	3	Furniture materials with recycled content	2
			Ecological paints	1
	We consider additional supplier qualification criteria	1	Supplier location	1
Manufacture of computers and peripheral equipment + Manufacture of electric lighting equipment + Manufacture of household appliances	We buy eco-friendly production materials	14	Components that ensure the energy efficiency of a product	8
			Construction materials with recycled content	4
			Construction materials with the content of raw materials of natural origin	2
	We consider additional supplier qualification criteria	6	Supplier location	2
			Supplier eco-friendly activities	1
			Possibility of order commingling	1
			ISO 14001 certification	2
	We pay attention to transportation packaging	1	Use of reusable packaging	1
Manufacture of building ceramics + Production of insulating materials + Production of paints and varnishes	We buy eco-friendly production materials	7	Production materials with recycled content	3
			Production materials with low content of hazardous chemicals	3
			Production materials with the content of raw materials of natural origin	1
	We consider additional supplier qualification criteria	2	Supplier location	1
			Possibility of order commingling	1

- considering additional pro-environmental criteria when qualifying suppliers (nine statements),
- paying attention to transport packaging (one statement).

The category "Actions in the field of supply" was assigned 39 citations, which accounted for less than 15 % of the citations in the database. This means that the surveyed companies are not particularly interested in sourcing eco-friendly production materials or considering additional pro-environmental criteria when qualifying suppliers. One surveyed company from the apparel industry admitted not considering any environmental aspects in their purchasing process, as they were only guided by price. Other surveyed apparel companies paid attention to the content of natural raw materials in fabrics and the content of natural dyes when purchasing production materials. It was indicated that they looked for the optimal composition of fabrics/dyes so that the designed/developed product was sufficiently durable. One manufacturer from the furniture industry admitted not being guided by environmental aspects when purchasing production materials. The remaining companies said they bought materials with recycled content. One respondent indicated that this was not their regular practice as "few customers have such expectations".

The next three industries manufacture energy-powered products. The most frequent pro-environmental purchasing criterion was "energy efficiency of components" (eight statements). One company representing the computer and peripheral manufacturing industry neither indicated this nor other environmental aspects as important in their purchasing process. Only one representative of this industry admitted to buying engineering plastics with recycled content. The others were not interested in this practice, focusing only on the best quality of materials. One of the respondents made the following statement: "Primarily, the utmost importance lies in the product's functionality, followed by the choice of components and materials that are more or less environmentally friendly". The remaining statements made by electrical lighting equipment and home appliance manufacturers indicated an interest in materials with recycled content (three statements).

The last three industries operate in the construction sector. One of the analysed companies from the building ceramics industry strongly denied buying materials with recycled content, explaining that "they are only interested in the best quality raw materials". The other two companies bought materials with recycled content but made it clear that the technology allowed for their use. In the case of manufacturers of insulation materials, each of the surveyed entities pointed to only one (each time different) environmental aspect related to purchasing ("production materials with low content of hazardous chemicals"/"production materials with recycled content"/"production materials with the content of raw materials of natural origin"). One of the surveyed companies from the paints and varnishes industry admitted that it did not consider any environmental aspects in the purchasing process, as price was the most important criterion. Other surveyed entities indicated making purchases by considering the content of chemicals and whether they posed a general threat to the environment.

3.2. Production processes

The second question of the interview concerned production processes. Three areas of action in the field of production processes were identified during the statement analysis (Table 3):

- lowering the level of production materials consumption (31 statements),
- lowering the level of conventional energy consumption (31 statements),
- lowering the level of water consumption (one statement).

The category "Actions in the field of production processes" was assigned 63 citations, accounting for just under 24 % of the citations in the database, indicating that, in general, aspects related to production (e.g., material consumption) were more important than aspects occurring in the supply chain (e.g., recycled content). Regarding the reduction of the consumption of production materials, respondents most often described the reuse of waste in the production process (14 statements). Although much less frequent, another activity in this area was using IT tools to facilitate the optimal usage of materials (six statements). To optimise the use of production materials, a few entities (four companies) produced products from waste, thus diversifying their activities. In the area of energy consumption reduction, two dominant activities were noted: the "use of photovoltaic panels" (12 statements) and "investment in machinery with low energy demand" (ten statements). One of the companies surveyed uses professional software that collects data on material and energy consumption and emissions to help control production performance. This is the only example of comprehensive monitoring of resource consumption in business operations. More often than not, companies could

Tab. 3. Actions in the field of production processes

Superior category	Major category	Frequency of occurrence	Subcategory	Frequency of occurrence
Actions in the field of production processes	We reduce the consumption of production materials	31	Reuse of waste (closed loop)	14
			Use of IT tools to facilitate optimal use of materials	6
			Investment in machinery to allow the most efficient material consumption	3
			Selection of materials to allow the most efficient use of them	3
			Monitoring of processes for waste minimisation (not IT-assisted)	2
			Preparation of intermediates to ensure efficiency in their use	1
			Processes improvement to eliminate non-conforming products	1
			Miniaturisation of product components	1
	We reduce the consumption of conventional energy	31	Use of photovoltaic panels	12
			Investment in machinery with low energy demand	10
			Optimisation of machine park working time	3
			Heat recovery	3
			Use of standby mode of machines and equipment	1
			Education of employees on energy-saving	2
	We reduce the consumption of water	1	Investment in machinery with low water demand	1

not describe in detail how they tracked materials used. One statement read: "From an economic perspective, everyone seeks to use as little energy, gas, or other things as possible. It is not written down or supervised in any way".

3.3. Distribution

The next question addressed the distribution topic. Two areas of action were identified in this field based on respondents' statements (Table 4):

- implementing pro-environmental solutions in the area of packaging (32 statements),
- implementing pro-environmental solutions in the area of transportation (23 statements).

The category "Actions in the field of distribution" was assigned 55 citations, accounting for about 21 % of citations in the database. To reduce the impact of the product distribution stage, most of the surveyed companies used packaging made of environmentally friendly materials (17 statements). In the second area of action in this field, the most popular was "optimisation of transport routes and cargo" (11 statements), followed by the "use of environmentally friendly fleet" (seven occurrences).

3.4. Product performance parameters

The next question concerned performance parameters for designed/developed products. Respondents were asked to describe actions they take to reduce the environmental impact of the product at the use stage. Two areas of activities were identified based on the responses (Table 5):

- implementing solutions to increase the durability/reliability (including extending the life of products) (68 statements),
- implementing solutions to reduce the intensity of resource use (19 statements).

The category "Actions in the field of a product's performance parameters" was assigned 87 citations, accounting for more than 32 % of the citations in the database and ranking this stage in the first place in terms of the number of actions taken to reduce the environmental impact of the products. One apparel company admitted to not having taken any actions to increase the durability/reliability of its products. The respondent's statement reads: "This may sound a bit brutal, but we don't care about using our products for as long as possible. It's not a priority for someone to use a garment for 20 years". Other apparel companies implement valuable activities leading to an increase in the durability/reliability of the products they offer, leading to an extended life cycle ("providing an offer for refresh/repair", "providing classic form and universal design", etc.). In the case of furniture manufacturers, each of the surveyed companies takes specific measures to increase the durability/reliability of the products, for example, "use of low-failure connection systems", "use of readily available damage-prone components or their provision at the point of sale".

Each of the surveyed companies in the computer and peripherals industry takes measures to reduce energy consumption while the product is active and/or in standby mode (they vary, e.g., installing motion sensors or using efficient batteries). Each of the surveyed companies also provides spare parts and has a product repair service on offer (beyond the warranty period). As in the case of computers and peripheral equipment manufacturers, the surveyed lighting producers try to reduce the energy intensity of their products. However, manufacturers in this industry are less active in the field of durability/reliability of their products than the previously analysed entities.

The surveyed household appliance manufacturers implement a wide variety of measures to reduce the resource intensity of their product use, and this applies to a broad range of products (e.g., providing

Tab. 4. Actions in the field of distribution

Superior category	Major category	Frequency of occurrence	Subcategory	Frequency of occurrence
Actions in the field of distribution	We implement pro-environmental solutions in the area of packaging	32	Use of packaging made of environmentally friendly materials	17
			Avoiding repackaging	8
			Reducing the weight of the packaging	1
			Giving up disposable packaging (partial)	6
	We implement pro-environmental solutions in the area of transportation	23	Optimisation of transport routes and cargo	11
			Use of an environmentally friendly vehicle fleet (electric cars or hybrids)	7
			Selection of courier company considering environmental aspects	3
			Transportation by rail	2

Tab. 5. Actions in the field of product performance parameters

Industry	Major category	Frequency of occurrence	Subcategory	Frequency of occurrence
Manufacture of other outerwear	We implement solutions to increase durability/reliability	17	Ensuring an optimal composition that gives the possibility of longer use	2
			Ensuring classic form and universal design	2
			Formulation of detailed instructions for care	2
			Providing a refresh/repair offer	2
			Providing models that adjust to buyers' size	2
			Use of modern print fixation technologies	1
			Strict control of the strength of the fabric and seams	2
			Use of readily available accessories or providing them at the point of sale	1
			Supporting actions of second-hand clothing resale	1
			Supporting the collection of unshredded clothing	1
			Organising post-season fairs (selling off old collections and unneeded fabrics)	1
Manufacture of other furniture	We implement solutions to increase durability/reliability	14	Use of low-failure connection systems	3
			Use of modern technology for the preparation of semi-finished products	1
			Ensure modularity of furniture	1
			Stability check after disassembly and reassembly	1
			Use of readily available damage-prone components or their provision at the point of sale	3
			Formulation of detailed maintenance instructions	3
			Providing a refresh/repair offer	2
Manufacture of computers and peripheral equipment + Manufacture of electric lighting equipment + Manufacture of household appliances	We implement solutions to increase durability/reliability	29	Increasing the efficiency of ventilation	2
			Use of technology that extends mechanical durability	5
			Ensuring the highest quality components	2
			Ensuring ease of upgrade/replacement	2
			Ease of repair and maintenance	1
			Detailed product testing and control of performance parameters	4
			Providing spare parts	6
			Providing a repair offer (beyond the warranty period)	7
	We implement solutions to reduce the resource intensity of use	13	Reducing energy consumption at usage	9
Manufacture of building ceramics + Production of insulating materials + Production of paints and varnishes	We implement solutions to increase durability/reliability	8	Use of modern material-strengthening technologies	3
			Use of modern technology that provides additional protection	3
			Use of materials that ensure a long shelf life	1
			Strict quality control of raw materials	1
	We implement solutions to reduce the resource intensity of use	5	Use of modern technology to ensure high insulation parameters	3
			Use of materials that ensure high product yield	1
			Training for wholesalers and contractors	1

a modern oven design to optimise operating time, providing a system to automatically set optimal freezing parameters, a function to retain water from the last rinse in the dishwasher, etc.). One company pointed out that "there will be something in each product range so that the customer can choose an even greener option for themselves than the regulations require". Manufacturers of household appliances indicated numerous measures to increase the durability/reliability of their products. One company's statement said: "We also don't care about introducing something that will break down immediately. We check everything down to the last detail, and we even do it with care, so to speak".

A surveyed manufacturer of building ceramics did not indicate specific measures leading to reducing the environmental impact of their product's use phase. Other companies used technology that provided increased insulation parameters. One statement was made regarding the use of material reinforcement technology and strict control of the raw material's quality, which, according to the respondent, is the most important in ensuring the durability of ceramic products. One insulation manufacturer said that they did not take additional measures to improve the product's performance aspects. According to the respondent, the way forward for the industry would be to develop a biodegradable product, but this is beyond the "capabilities of a small company". The second surveyed manufacturer of insulation materials takes steps to improve its insulation performance, ensuring that products are continuously developed in this regard. This company also uses innovative additives to improve the strength of materials. The third company implements technological solutions to improve insulation parameters in addition to using technology that increases the durability of the offered product. In the statements of the surveyed paint and varnish manufacturers, the use of technology to ensure high product durability came up twice. Each of the surveyed companies reiterated the importance of reducing harmful air emissions during product application and ensured that this aspect is considered when purchasing production materials.

3.5. Final disposal

The last question concerned reducing the environmental impact of the product's final disposal. Two areas of action were identified in the responses of the surveyed companies (Table 6):

- implementing solutions to facilitate disassembly and recycling (20 statements),
- taking additional organisational measures (four statements).

There were 24 citations assigned to the overarching category "Actions in the field of final disposal", which accounted for less than 10 % of the citations in the database. This is certainly the most difficult stage for the surveyed companies to counteract environmental damage. Seven surveyed companies did not take any initiatives to reduce the environmental impact of their product's end-of-life (no such far-reaching passivity was noted for the other stages). Among the identified activities, it is worth noting the possibility of returning used products and their recycling/recovery within the scope of the manufacturer's operations (five statements). Seven respondent statements also included the issue of ensuring that disassembly can be carried out using common hand tools and unskilled labour.

Tab. 6. Actions in the field of final disposal

Superior category	Major category	Frequency of occurrence	Subcategory	Frequency of occurrence
Actions in the field of final disposal	We implement solutions to facilitate disassembly and recycling	20	Ensuring collection of used products and recycling/recovery	5
			Ensuring the possibility of post-assembly waste return and recycling /recovery	2
			Ensuring that dismantling can be carried out using common hand tools and unskilled labour	7
			Providing dismantling service	1
			Use of homogeneous, recyclable materials	4
			Elimination of coatings that are difficult in the final processing stage	1
	We take additional organisational measures	4	Collection of used equipment (on its own)	4

Tab. 7. Stages for which advanced actions are implemented

Industry	Number of employees	stages
Manufacture of other outerwear	Below 10	Product use
	Up 250	Product use
Manufacture of other furniture	50–250	Production
	50–250	Production
Manufacture of electric lighting equipment	10–49	Distribution
Manufacture of household appliances	Up 250	Product use Final disposal
	Up 250	Product use
	50–250	Product use
Manufacture of building ceramics	Up 250	Production
Production of insulating materials	Up 250	Product use Final disposal

4. Discussion of the results

It seems indisputable that companies should consider the life cycle perspective in pro-environmental activities. It involves identifying and prioritising environmental aspects in a product life cycle, determining the most critical, and implementing basic measures to address them. Critical points (hot spots) in the life cycle of various products are described in the literature (e.g., Joachimiak-Lechman et al., 2017; Joachimiak-Lechman et al., 2019). However, the range of actions companies from different industries apply to reduce the impact of product life cycle has not been studied in depth. The degree to which companies consider the life cycle perspective, i.e., a degree understood as the variety of measures taken and their complexity, depends on a number of internal factors. In this area, product specificity plays an important role.

All surveyed companies undertake activities to reduce the environmental impacts occurring at least at two stages in the life cycle of their products. Twelve companies include all life cycle stages in their product design and development practices. Seven companies exclude only one stage. The activities vary in scope. The final disposal stage is the most difficult issue for the surveyed companies. A survey of 300 manufacturing companies in Spain concluded that the most frequent practice in product design was the design for recycling (Triguero et al., 2023). The study presented in this paper shows that the surveyed companies pay the most attention to the product performance parameters.

Table 7 indicates companies with advanced actions and their implementation stages. Ten companies undertook actions that could be considered advanced. Six of these companies use advanced activities to address the product's use phase, meaning that manufacturers reduce the used product's environmental impact by considering and implementing complex solutions. Two companies undertake such activities at more than one life cycle stage (use and final disposal). Based on other studies (Siwiec et al., 2023), paying attention to product performance parameters involves competing on quality.

Table 7 shows the size of companies undertaking advanced activities. The company size is an important factor influencing involvement in pro-environmental activities, which was also concluded by Dostatni et al. (2024). As mentioned, six large business entities participated in the interviews presented in this paper. Their activities focusing on the life cycle perspective varied in scope, and not all entities showed particular commitment. Two out of the three surveyed household appliance manufacturers were large entities. In their statements, many examples illustrated efforts to reduce the environmental impact of product use. However, one-third of household appliance manufacturers belonging to the SME sector were equally active in improving the environmental aspects of this stage. A similar situation was observed in the apparel industry: a micro-company showed a far-reaching commitment to product development in terms of life cycle aspects, which was not far behind the large company's. Consequently, while it is easier for large entities to undertake such activities, the key element is environmental awareness. The following statement was made by a representative of a micro-enterprise in the apparel industry: "Every company should focus on minimising the negative impact on the environment. We operate in terms of eco-design all the time, and regardless of the financial situation, that's just the way it is".

This study is unique as it analysed different manufacturing sectors. Due to the diverse characteristics of the surveyed products, a comparison of the selected industries is difficult. Nonetheless, a few general points are worth mentioning. Manufacturers of household appliances and other energy-powered products show a relatively high level of interest in environmental aspects of the life cycle. This is probably because their products are characterised by many parameters that can be improved. Also, eco-design requirements are significant; thus, manufacturers have to change their thinking about the products they offer. All surveyed manufacturers of energy-powered products are taking steps to reduce the intensity of used energy. The apparel and furniture industries are not bound by eco-design requirements at the moment. Therefore, the improvements focusing on the product life cycle are driven by the need to adapt to potential trends. In the case of the apparel industry, two of the three surveyed companies showed a noteworthy interest in improving the environmental aspects of the life cycle of the products (especially in the field of durability/reliability). Less interest in the life cycle perspective was demonstrated by manufacturers of the products used in the construction industry. Companies in this industry reported a relatively narrow range of performance improvement opportunities.

Conclusions

The interview focused on the actions surveyed companies took in product policy on life cycle thinking. The questions were asked in the context of product design or development, but respondents often spoke about pro-environmental activities in a broader context. Some surveyed companies were unaware of the measures they took for pro-environmental product development. Based on the responses, many surveyed entities did not link their product-related environmental actions directly with eco-design. The study provided evidence that companies mainly implemented pro-environmental practices for pragmatic reasons.

The evaluation of product-focused pro-environmental activities should consider whether the crucial stage that requires appropriate measures is given priority in these activities. Only one of the interviewed companies (an apparel industry representative) did not pay attention to environmental aspects critical to the product life cycle. In its case, the idea of life cycle thinking was not present. Other companies participating in the study considered the life cycle perspective when designing or further developing the existing products by considering environmental aspects that are the hot spots in the product life cycle. However, the activities varied in scope. Ten entities implemented complex activities targeting various aspects (not only the most relevant) of the product life cycle.

All the surveyed entities implement pro-environmental activities in production processes, and most concern several aspects (e.g., material and energy consumption). In the statements, respondents clearly emphasised that pursuing optimal resource consumption was associated with rising production costs. In addition to production process-oriented activities, each surveyed company undertakes activities related to other life cycle stages (at least one). This indicates a new corporate approach that goes beyond the operational boundaries of the organisation. Based on the results, it can be concluded that the surveyed companies take the greatest number of actions to reduce the environmental impact of the use stage of products, mostly aiming to increase their durability/reliability. Respondents emphasised that it ensured quality and guaranteed customer satisfaction. Respondents showed relatively little interest in using recycled or natural raw materials. Some surveyed entities thought it would negatively affect the product quality. None of the surveyed companies asserted that environmental criteria of supply were a primary issue for them (more important than price).

The paper proves that eco-design requirements are an unquestionable driver for activities from a life cycle perspective. Eco-design requirements for energy-powered products impose many obligations on manufacturers regarding environmental aspects. Even though the interview did not explicitly intend to assess compliance with legal requirements, many respondent statements indicated that they were indeed complying and, in certain instances, going beyond what was required. All surveyed manufacturers of energy-powered products took measures to reduce energy intensity when the product is active and/or in standby mode. They were less active, e.g., in ensuring product durability/reliability (except for home appliance manufacturers, which take numerous measures in this area) and in facilitating disassembly and recycling. Importantly, these issues will likely be included in the expanded eco-design regulation, so the surveyed companies were expected to pay more attention to them.

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