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EDITORIAL OFFICE

Bialystok University of Technology
Wiejska 45A, 15-351 Bialystok, Poland
Phone: (+4885) 746 9825
Fax: (+4885) 663 1988
www.empas.pb.edu.pl

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Employee scheduling and maintenance planning for safety systems at the remotely located oil and gas industrial facilities

Yury Redutskiy Marina Balycheva
Hendrik Dybdahl

ABSTRACT
The safety of operations is vital in any process in the oil and gas sector, especially given that increasingly more hydrocarbon reserves are discovered in non-conventional remote and Arctic locations. Safety systems are designed as a part of a complex IT system for process control. The design of these systems is conducted in the form of an engineering project. This research presents a decision-making framework to facilitate formulating clear and comprehensive recommendations for the requirements specification developed for the safety systems. The contribution of this research to the strategic planning area of IT solutions for hazardous industrial facilities is integrating the problems of designing a safety system, planning its maintenance, and scheduling the employees to conduct the required maintenance. With this joint decision-making, it is possible to explore trade-offs between investments into the systems' complexity and workforce-related expenditures throughout the solution's lifecycle. The reliability modelling is conducted with the help of Markov analysis. The multi-objective decision-making framework is employed to deduce straightforward requirements to the safety system design, maintenance strategy, and workforce organisation. This research is relevant to managing the petroleum sector engineering projects with regard to the design of technological solutions.

KEY WORDS
employee scheduling, engineering project management, maintenance planning in the oil and gas industry, remote and arctic location, requirements specification, safety systems

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Yury Redutskiy

Molde University College, Norway
ORCID 0000-0002-3385-1712

Corresponding author:
e-mail: yury.redutskiy@himolde.no

Marina Balycheva

National University of Oil and Gas
ORCID 0000-0003-4713-4295

Hendrik Dybdahl

Molde University College, Norway
ORCID 0000-0001-6391-7842

Introduction

The oil and gas production rates have increased over the past decades (BP, 2022). Increasingly more hydrocarbon reserves are being discovered in non-conventional environments, such as remote areas, deep-water offshore locations, and the Arctic region (Mellemvik et al., 2015). A study conducted by Bird et al. (2008) demonstrates that roughly 22 % of the remaining world's oil and gas reserves are located in the Arctic region, and 84 % are situated offshore.

Redutskiy, Y., Balycheva, M., & Dybdahl, H. (2022). Employee scheduling and maintenance planning for safety systems at the remotely located oil and gas industrial facilities. *Engineering Management in Production and Services, 14*(4), 1-21. doi: 10.2478/emj-2022-0028

These non-conventional environments pose considerable logistic challenges due to the climate in the north and the remoteness of the new production sites from the populated areas and large industrial centres.

Operations conducted on any oil and gas facility are associated with risks and possibilities of incidents. The consequences of an incident affect workers, assets/facilities, and the environment in terms of the ecosystem and the people in the nearby locations. The safety of operations is vital in any process along the oil and gas value chain: production, processing, transportation, refining, and distribution. Any oil and gas facility may be viewed as a hazardous industrial facility, and therefore, much attention has to be paid to its operational safety. To deal with this issue, automated control systems are put in place to monitor process parameters and, if necessary, shut down the operations. Such systems are called safety instrumented systems (SIS). There are usually several SISs deployed for any given technology to implement various safety functions. Some SISs are put in place to prevent hazardous situations, while others aim to mitigate the consequences if an incident happens (Boudreaux, 2010). In the process industry, among the various SISs deployed for a particular solution, emergency shutdown (ESD) systems are considered vital since they ensure the highest risk reduction among the preventive safety measures (Torres-Echeverria, 2009; CCPS, 2010). Therefore, this research focuses on ESD systems; however, the presented ideas and modelling approaches apply to any SIS.

Technological solutions and the necessary safety instrumentation are developed as an engineering project (Fig. 1). A new project is always launched by an exploration and production (E&P) operator. E&P operators are usually rather big companies with steady incoming cash flows, and therefore, they are not afraid to take some risks. Examples of such companies are Equinor, BP, Shell, Chevron, ExxonMobil, Petrobras, etc. The first step in initiating a new industrial facility is conceptual design. During this phase, various technical and technological possibilities are explored for the planned facilities. Further, an engineering contractor company's services are employed to develop and implement the actual engineering solution. At this stage, the requirements specification for the planned facility is developed, discussed, and revised. An important part of formulating the requirements specification is considering the safety regulations imposed by the national authorities. The next step is the detailed engineering design, followed by testing and commissioning. Afterwards, the longest-running phase of the project begins: it is the operations and maintenance phase when the developed solution is put to use for the E&P operator. To run operations and adequately maintain the developed solution in non-conventional remote locations, the E&P operator usually establishes a subsidiary somewhat close to the production site and hires the local workforce.

Three stakeholder categories may be identified as the project goes through the earlier described phases (Redutskiy, 2017). The first is national authorities in charge of the hydrocarbon reserves and performing regulatory functions when it comes to approving the establishment of hazardous facilities and providing general requirements for their safety. The second stakeholder is the E&P operator, investing in the development of the hydrocarbon deposits by building the processing, transportation, and distribution facilities. And finally, the engineering contractors are responsible for developing the technological facilities and IT solutions for process control. Each of these stakeholders has its priorities for the project. The national authorities aim to ensure the appropriate safety level for planned hazardous industrial facilities. Engineering companies strive to minimise lifecycle costs since they usually participate in competitive bidding to be hired for their service. The operating company's priorities include minimisation of lifecycle cost and facility downtime since they strive for uninterrupted operations to gain revenues.

Among the described project phases, special attention should be paid to the requirement specifications. The study (HSE, 2003) examined a sample of incidents in the petroleum sector with respect to the phases of the engineering project implementation in an attempt to determine where the primary causes of the incidents lie. This study concluded that almost half of the examined incidents were due to inadequacies in requirement specification for the safety systems. Too general, vague, or insufficient requirements result in the faulty design of the automated systems indented to ensure the safety of hazardous operations.

To make SIS requirements clear and sufficient, first and foremost, SIS-related safety measures must be examined. For this, one must refer to the international standards on industrial safety: IEC 61508 (1998) and IEC 61511 (2003). These standards demonstrate how specific equipment, architectures, and maintenance choices lead to achieving a specified safety level. The standards IEC 61508 and IEC 61511 are adopted worldwide, and they are the basis for national regulations, e.g., STC Industrial Safety

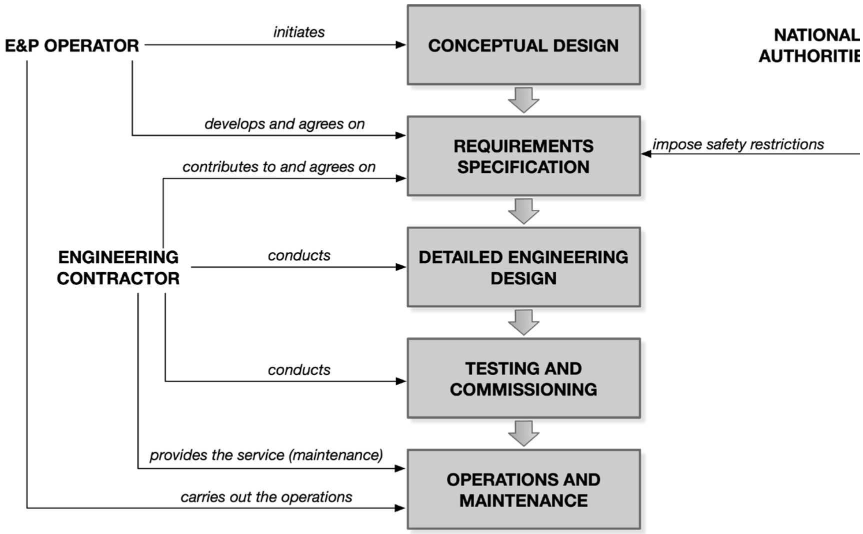

Fig. 1. Stakeholders and phases of the oil and gas engineering projects

Source: elaborated by the authors based on Redutskiy (2017).

(2014) in Russia and NOG-070 (2018) in Norway, which determine the safety level for various hazardous facilities and units to be achieved to operate properly. These requirements for the safety level are still relatively broad. Therefore, the issue of coming up with comprehensive yet straightforward requirement specifications should, perhaps, cover the safety measures inherent in SISs (i.e., instrumentation, architectures, and maintenance strategy) as clearly as possible. That way, these requirements may become a reasonably good starting point for the detailed design of a given SIS.

To ensure the proper function of the developed SIS, the aspect of maintaining the developed solution must be considered together with the issues of the SIS design. To perform adequate maintenance for the modern-day oil and gas industrial facilities faced with the challenges of non-conventional remote environments, it is essential to organise and train the workforce properly. Workforce management in remote areas is fairly costly, and so there is a need for appropriate decision-making when planning the maintenance and scheduling the repairpersons' transportation. The production and engineering companies strive to reduce their expenditures and, therefore, aim for cost-efficient maintenance. There is a need for a detailed plan of when the workers should arrive and how long they should work on each shift.

This research aims to develop a decision-making framework to facilitate the formulation of comprehensive requirement specifications for the safety instrumented systems. The decision-making should simultaneously cover the issues of the SIS design, maintenance, and workforce-related choices relevant to modern-day remotely located industrial facilities.

1. Overview of the research area

The research concerning industrial safety systems is mainly based on the reliability theory and the approaches to modelling the failures in an SIS. The international standards IEC 61508 (1998) and IEC 61511 (2003) present a comprehensive overview of the basic ideas and modelling approaches relevant to SIS design and maintenance. Among several widely used modelling techniques, the standards focus primarily on simplified equations (SE), reliability block diagrams (RBD), and fault tree analysis (FTA). Despite the wide application of the mentioned techniques, they primarily focus on various mechanisms of instrumentation failures and do not allow including such important aspects as device repairs and technological incidents. Due to these limitations of the SE, RBD, and FTA methods, some researchers choose to employ more complex and dynamic modelling approaches, such as Markov analysis (MA), which allows including device failures and repairs as well as technological incidents and restorations into one modelling framework. Examples of MA application may be found in the literature (Bukowski, 2006; Jin et al., 2011; Redutskiy, 2017; Srivastav et al., 2020). A reader interested in the details and comparison of various modelling and design approaches relevant to safety instrumented systems is encouraged to refer to a review by Gabriel et al. (2018) or the book by Kuo and Zuo (2003).

In addition to the viewpoint of safety and reliability modelling of the SIS performance, this paper addresses choosing the appropriate maintenance strategy together with the workforce organisation to conduct the required maintenance. The problems related to workforce organisation and employee scheduling have been covered extensively over the past few decades for various applications, such as home nurse visitations, technician service scheduling, etc. However, strategic planning of the safety solution for remotely located industrial facilities and planning the employee shift work has not yet gained the proper attention in the literature. The research (Castillo-Salazar, 2016) provides an extensive overview of employee scheduling models and details relevant to real-life applications. Among these problem settings, the authors distinguish a class of problems named "workforce scheduling and routing problems". The problems in this category address the requirement for personnel to perform a given service at a given location. An important feature of this problem category is that the demand has to be satisfied precisely, unlike in many other real-life settings (e.g., tech-support call centres where the demand for personnel is considered stochastic). This particular approach to modelling the demand for servicepersons or service crews is relevant to the oil and gas industry since the maintenance requirements are usually provided in the form of a timeframe within which the maintenance must be completed so that the operations would proceed safely. The issues of hazards and industrial safety prompt the demand for the required maintenance to be met exactly. This approach to fulfilling the demand requirement is usually modelled based on the set-covering employee scheduling problem formulation proposed by (Dantzig, 1954). An overview of some issues pertaining to these problem contexts may be found in research (Soriano et al., 2020). Among the pool of research specific to the non-conventional and remote locations in the petroleum sector, several research papers may be noted (Hermeto, Ferreira, & Bahiense, 2014; Bastos, Fleck, & Martinelli, 2020; Vieira et al., 2021; De La Vega et al., 2022).

The overwhelming majority of the literature on workforce scheduling for maintenance and maintenance as a safety aspect is quite strongly divided into these two respective streams. The first (Hermeto, Ferreira, & Bahiense, 2014; Bastos, Fleck, & Martinelli, 2020; Vieira et al., 2021; De La Vega et al., 2022) focuses primarily on the tactical or operational details of employee scheduling and transport utilisation, primarily helicopters. The second focuses on the engineering details of safety, i.e., the safety system design (which corresponds to the strategic planning level). Thus, maintenance is considered merely a rather abstract concept or a very rough estimation of one operational-level detail. Notably, several research papers within this stream (Torres-Echeverria, 2009; Torres-Echeverria, Martorell & Thompson, 2012; Zhao, Si & Cai, 2019) employ multi-objective optimisation based on meta-heuristic algorithms. These papers engage in very detailed studying of the algorithm modalities and result in the produced Pareto optimal set with respect to the conflicting or non-conflicting relationship between various objectives. The results, however, could be used to draw certain real-life practical conclusions, which is one of the gaps this research aims to address.

The research (Helber & Henken, 2010) stresses the importance of addressing the issues that directly impact personnel requirements and workforce-related decisions. For the problem addressed in this research, the design and maintenance strategy choices for the planned SIS are the factors directly influencing the demand for the employees required to conduct the system maintenance. Given the specifics of maintaining a remotely located industrial facility, workforce-related costs play an especially significant role. Therefore, balancing these design and maintenance scheduling aspects should provide valuable insight into decision-making from the strategic planning viewpoint.

Upon conducting an extensive literature search, the authors of this paper have not found any academic articles that would address the two mentioned research gaps other than those produced by the research group (Redutskiy, 2018; Redutskiy et al., 2021) whose work is continued here.

This paper aims to develop a decision-making framework that would integrate the problems of designing the SIS, planning its maintenance, and scheduling the employees to conduct the required maintenance. With this joint decision-making, it is possible to explore the trade-offs between the investments into the complexity of the SIS (and thereby, its reliability) and the workforce-related expenditures, such as training costs, salaries, travel costs, bonuses for longer shifts and so on throughout the entire solution's lifecycle. The reliability modelling is conducted with the help of Markov analysis. The integer programming model is developed to solve the employee scheduling problem. Finally, the lifecycle cost covering the mentioned aspects of the SIS is evaluated. To apply the model for deducing comprehensive requirements for the SIS design, maintenance strategy, and workforce organisation, a multi-objective optimisation is employed to produce several solutions, that is, a Pareto-front, to further examine their features and draw the appropriate conclusions.

2. Problem setting

The international standards IEC 61508 and IEC 61511 introduce the term safety instrumented system (SIS), defining them through their structure. An SIS consists of the same essential parts as any other automated system. The structure's (Fig. 2a) essential parts are explained further:

- process value transmitters, or sensors, are put in place to identify the state of the technology by measuring necessary process parameters;
- logic solvers, or programmable logic controllers (PLC), are industrial computers programmed to implement specific algorithms. The PLC's input modules gather the measurement information from the sensors, and the output modules deliver the control signal to the next subsystem;
- final control elements, or actuators, are put in place to affect the processes by, for example, making valves open or close, making pump drives work at a particular load or turning some electrical equipment on or off by the use of switches.

When designing any real-life SIS for a given technology, an important point is the choice of devices — sensors, controllers, and actuators — for the automated safety system. All device types are presented on the market by several analogous alternatives from various brands of automation instrumentation: Rockwell, Emerson, General Electric, Honeywell, Siemens, and others. Even though different brand devices may physically implement the same action, the reliability characteristics of these analogous alternatives from different instrumentation vendors vary considerably. Therefore, the choice of instrumentation, that is, particular device models for the subsystems of the developed safety solution, is an important issue of the SIS design.

Another important point with respect to SIS design is that in reality, each of the blocks in Fig. 2a — process value transmitters, logic solvers, and final control elements — may have more than one device implementing the same function at the same time, which is quite common for SISs. This design approach is called redundancy. The aim of using more than one component for the subsystems is to improve the subsystem's overall reliability: while some devices fail, others may continue performing their designated function. Redundancy of a subsystem is usually expressed through its M-out-of-N (MooN) architecture (Fig. 2b). In this notation, N stands for the total number of components in the architecture, and M represents the number of devices in the architecture that must operate, so that the whole architecture would perform properly.

A problem concerning redundancy is that, in some cases, multiple devices within a subsystem may fail because of the same cause or stress. It may be an accidental power cut to these identical devices or physical damage to a certain technological unit. This phenomenon is referred to as common-cause failure (CCF). To reduce the possible influence of CCF, additional device separation may be introduced within the MooN architecture. In Fig. 2b, it is marked by dashed lines between components.

The SIS structure depicted in Fig. 2a is a simplification aimed at reflecting the key blocks of an SIS. Real-life automated systems monitor many process parameters simultaneously and deliver their values to the PLC. Each of these sensor subsystems is responsible for identifying its potential incident. Therefore, instead of just one block of process value transmitters, in real-life solutions, there are several sensor subsystems, as demonstrated in Fig. 2c. There are also several actuators controlled by the PLC. It means that in case an incident is identified (and therefore, there is a demand for the safety systems to perform their function, e.g., technology shutdown), multiple actions are taken: some equipment must be turned off, pumps must be stopped, some valves must close, while others must open, and so on.

From the viewpoint of reliability modelling (reliability block diagrams), the structure in Fig. 2c implies a sequential connection of the blocks representing the SIS subsystems (Fig. 2d). The idea of the sequentially connected functional blocks is that all of the SIS subsystems have to be operating properly for the SIS to be able to perform its function.

To summarise, the issues of designing an SIS include the following:

- device model choice for the sensors, controllers, and actuators;

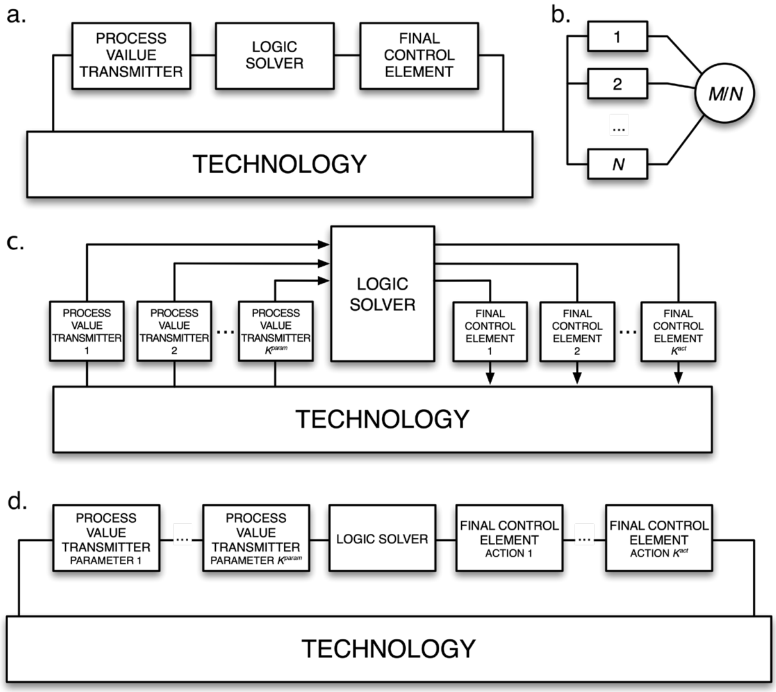

Fig. 2. SIS structure: a. Automated control loop. b. *MooN* redundancy architecture. c. Structure of a realistic SIS. d. Sequential structure of the SIS blocks is due to the reliability block-diagram principles

Source: elaborated by the authors based on IEC 61508 (1998) and IEC 61511 (2003).

- redundancy architecture choices, i.e., MooN architectures for each subsystem;
- the decision of whether to use additional device separation or not.

The problem of the SIS design should benefit from considering planning the maintenance of the SIS within the same decision-making framework. Both design and maintenance are associated with considerable expenditures and, at the same time, influence the reliability of the developed safety system. The maintenance of the safety systems is usually conducted in two forms. First, continuous maintenance is performed while the technology is running. The purpose of continuous maintenance is to address the identified failures. And second, there are also maintenance tests (or proof tests), which are conducted periodically. Such tests aim to address the failures that go undetected while the process runs.

Simultaneous consideration of the design and maintenance decisions helps explore the reliability and economic trade-offs between the decision alternatives. Highly reliable devices or architectures with significant redundancy will likely require rare maintenance. However, such solutions may turn out to be expensive. Simpler solutions with cheaper devices, on the other hand, are likely to require frequent maintenance. The more effort is associated with the instrumentation maintenance, the bigger some cost components are. For example, labour costs play a significant role in the solution's lifecycle if the operations in remote locations are considered, if only due to considerable travel costs associated with the maintenance personnel shift work. Also, such cost components as expenditures for spare parts and various maintenance tools can become quite high for a system with insufficient reliability. Yet another aspect of SIS performance evaluation is estimated losses due to the technology downtime associated with instrumentation overhauls.

So far, only the issue of maintenance frequency (which is usually expressed in the form of test interval TI) has been brought up. Besides TI, a part of planning the maintenance strategy is to organise testing in a certain manner. Fig. 3 shows three approaches to proof testing or maintenance policies. They are parallel, sequential, and staggered maintenance policies. Parallel testing implies that all the SIS instrumentation gets tested and repaired simultaneously. The sequential policy means that within each subsystem, the components get tested one after another. Of course, parallel testing requires considerably more staff to be present for the testing rather than sequential testing. On the other hand, the testing itself takes less time (hence, less facility downtime) if parallel

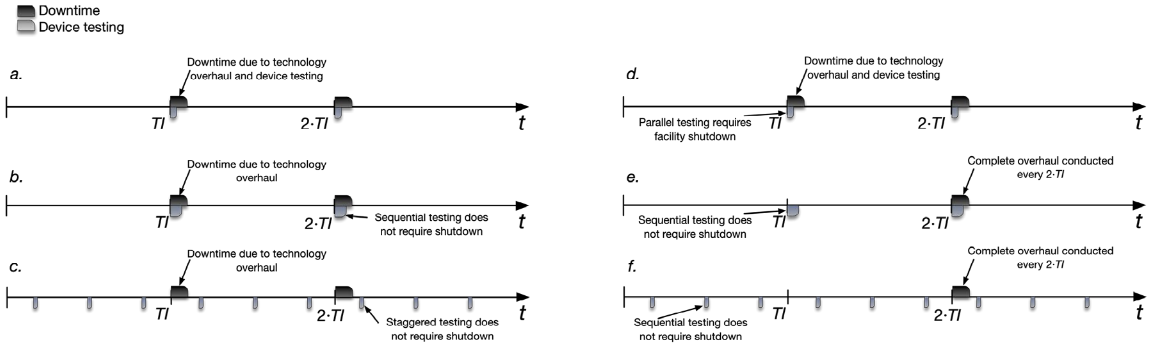

Fig. 3. Examples of proof testing policies. a, d: parallel proof testing policy; b, e: sequential proof testing policy; c, f: staggered proof testing policy for one subsystem with the tests uniformly distributed within *TI*. a, b, c: technology overhaul period equals *TI*; d, e, f: technology overhaul period equals 2·*TI*

Source: elaborated by the authors based on Torres-Echeverria (2009).

testing is chosen. Yet another approach to proof testing is the staggered policy when the subsystem's components are tested at separate points in time within the test interval. It should be mentioned that there are many more approaches to proof testing than the three described here. The international standards, however, usually recommend testing the entire SIS within the predefined timeframe. This is why, in this research, the decision-making is limited to the instrumentation testing approaches demonstrated in Fig. 3.

As Fig. 3 demonstrates, in addition to maintaining the SIS instrumentation, the technological facilities should also be maintained at certain points. The model presented further considers the period between two consecutive technological overhauls to be equal to the value of TI or a multiple of TI.

This paper continues previous research (Redutskiy, 2017; Redutskiy, 2018; Redutskiy et al., 2021). Here, Markov analysis is applied to evaluate the safety system's performance in terms of reliability. This particular type of reliability analysis is chosen due to its versatility, that is, the capability to incorporate the occurrence of events of various nature, such as device failures and repairs, as well as technological incidents and restorations. These stochastic events are assumed to be exponentially distributed, that is, they occur with a constant frequency or rate, as demonstrated in expression (1). The assumption of the exponential distribution of failures and incidents is proven valid for systems that include many electric and electronic devices (Goble, 2010). When it comes to the validity of the exponential distribution for repairs and restorations, Bukowski (2006) showed that such an assumption might turn out to be optimistic, which is hardly suitable for long-term SIS and maintenance planning. As mentioned, the research (Redutskiy, 2017) is continued here. That paper proposes a simple approach to the distribution of repairs and restorations into a pessimistic assumption by utilising the maximum limits set for the repair times instead of the average repair times.

$$P^{event}(t) = 1 - e^{-\lambda \cdot t}, t \geq 0 \qquad (1)$$

Fig. 4 shows the classification of failures assumed for this research. All safe failures are considered to be detected failures, which is a reasonable assumption for an SIS such as an emergency shutdown (ESD) system. If a safe failure occurs, the ESD must shut down the technology.

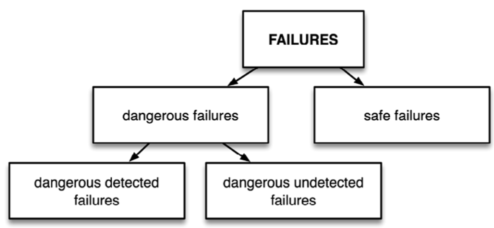

Fig. 4. Classification of the failure modes assumed for this research

Source: adapted from Redutskiy (2017).

To quantify the safety of a certain SIS solution, the most important reliability indicator is the average probability of failure on demand (PFDavg). The requirements for PFDavg in the regulations are normally set in the form of a safety integrity level (SIL). According to regulations set by national authorities (e.g., STC Industrial Safety, 2014; NOG-070, 2018), the SIL requirement SIL 3 is the main process within the oil and gas production, processing, transportation, and refining technology. Another safety indicator considered in this research is the expected facility downtime (DT). It reflects the operating company's perspective since the operator's goal is profit in the long run; therefore, they strive for the smooth operation of their technology.

As stated earlier, the maintenance of the SIS solutions is crucial to their performance. The maintenance is performed by engineers specialising in automated systems; therefore, the problem of organising the workforce to implement the required maintenance strategies becomes relevant for the modern-day facilities located in remote, Arctic and offshore areas far from cities and large industrial centres. In many cases, a subsidiary is established by the operating company somewhat close to the production site, and the local engineers are trained at this facility on the SIS and facility maintenance.

Still, when the engineers have to be transported to the remotely located facility and back, it may involve several transportation modes and legs. To address the workforce organisation issues, this research applies a modification of the set-covering formulation of employee scheduling first proposed by Dantzig (1954). The model determines how many workers should take a trip of a particular duration starting at a particular time. Employee scheduling utilises the approach of "hard demand constraints", meaning that the demand must be met exactly. This is often the case for oil and gas industrial facilities since the maintenance must be completed within a predefined timeframe. These timeframe requirements are used in the model together with the SIS design to calculate the weekly demand of workers required to be present at the facility during each week of the planning horizon.

The employee scheduling model in this research accounts for certain shift work specifics relevant to the petroleum sector. The model addresses compensation to the workers if their shifts are longer than the "standard" shift. It has become customary in the industry for companies to award workers who spend more time on their shifts with larger yearly or quarterly bonuses. The model also accounts for the daily work schedule, which depends on the size of the maintenance crew. There are two different options for the daily work schedules; these are 8-hour and 12-hour schedules. In the first option, three workers in the maintenance crew are required to ensure con-

Tab. 1. SIL requirements

SIL	Risk reduction requirement		Fault tolerance requirement[b] for logic solvers			Fault tolerance requirement[b] for sensors and actuators
	PFD_{AVG}	RRF[a]	with SFF<60%	with 60% ≤ SFF < 90%	with SFF ≥ 90%	
1	$[10^{-2}, 10^{-1})$	$(10, 10^2]$	1	0	0	0
2	$[10^{-3}, 10^{-2})$	$(10^2, 10^3]$	2	1	0	1
3	$[10^{-4}, 10^{-3})$	$(10^3, 10^4]$	3	2	1	2
4	$[10^{-5}, 10^{-4})$	$(10^4, 10^5]$	special requirements			special requirements

a. Risk reduction factor. b. Refer to IEC 61508 (1998) for an explanation of fault tolerance requirement and safe failure fraction (SFF
Source: IEC 61508 (1998) and IEC 61511 (2003).

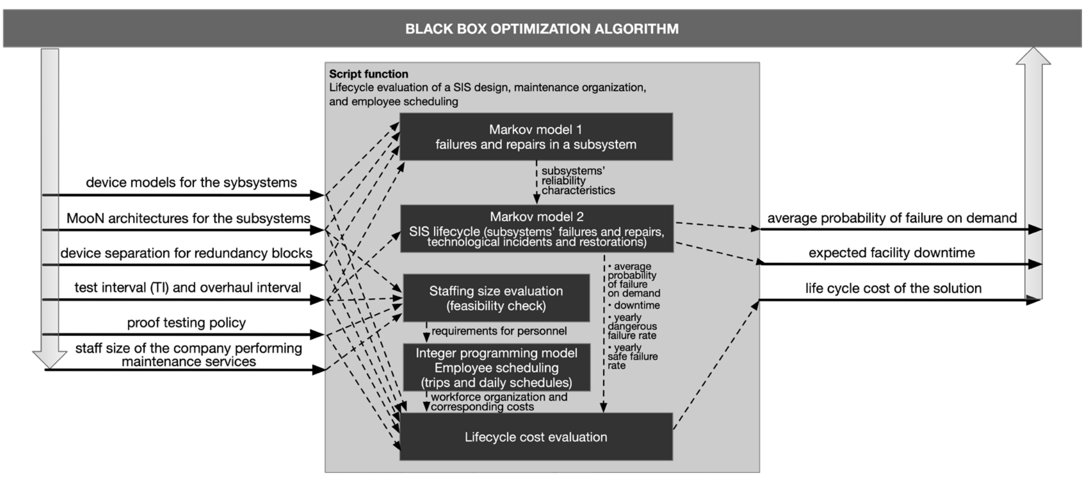

Fig. 5. Multi-objective decision-making framework

Source: based on Redutskiy (2018).

tinuous 24-hour service. In the latter option, only two workers are needed to ensure the service level. In addition, the model accounts for the establishment of a workforce of a given size, providing salaries and limiting the amount of time spent on trips to the remotely located facilities.

Another distinctive characteristic of the employee scheduling approach used in this research is that the developed model accounts for individual employees' yearly travel schedules instead of merely determining the collective number of crews required to take a certain trip. Accounting for each employee helps to determine the engineering staff size precisely to properly limit the time each worker spends at the remote facility and to ensure the availability of vacations for each employee.

The decision-making framework developed in this research consists of different blocks addressing various aspects of planning an SIS in the long-term perspective. The modelling blocks, the decision variables, and the objective functions for the optimisation problem are reflected in Fig. 5.

Decision variables:

- particular device models for each subsystem of the SIS;
- redundancy architecture (MooN) for each subsystem;
- the decision of whether to use additional electric separation for each subsystem or not;
- test interval (TI) for periodic proof testing and overhaul interval as a multiple of TI;
- proof testing policy (parallel, sequential, or staggered) for each subsystem;
- staff size of the engineering company performing the maintenance.
- Since there are different stakeholders with diverging viewpoints, which need to be considered when designing and planning SIS maintenance, the following objectives are used for decision-making:
- SIS's average probability of failure on demand;
- expected facility downtime;
- the lifecycle cost of an SIS operating for a particular hazardous technology.

2.1. Modelling assumptions

The lifecycle viewpoint suggested in the earlier research (Redutskiy, 2017; Redutskiy, 2018) is used for the strategic planning of the automated safety solutions employed for hazardous oil and gas industry technologies. This research, however, includes a more detailed view of the maintenance policies by incorporating the details of parallel, sequential, and staggered proof testing policies into the modelling and decision-making framework.

The assumptions made for further modelling are as follows:

- The instrumentation failures are assumed to be random, and the classification shown in Fig. 4 is assumed for these failures. Systematic failures are excluded from consideration as these failures must be resolved before the operations begin.
- The notations DD, DU, and ST are used in the models to distinguish dangerous detected, dangerous undetected failures, and spurious trips (or safe failures), according to the classification in Fig. 4.
- Instrumentation failures and repairs, as well as technological incidents and restorations, are considered to be exponentially distributed.
- Whenever a device failure is revealed during the course of operations, the failure is resolved within a predefined timeframe.
- All devices are tested within the period called test interval (TI). These proof tests are considered perfect, i.e., it is assumed that the undetected failures are resolved after a proof test.
- A major overhaul is conducted with a period which is a multiple of TI.
- The requirement for the number of servicepersons to be available at the facility at any time is computed with respect to the chosen architectures of the SIS subsystems and the chosen proof-testing policies.
- All possible trip starting times and the trip durations of one, two, four, and six weeks are considered along with their associated costs.
- A set-covering employee scheduling model is used to determine the number of maintenance crews required to go on particular trips and work following particular daily schedules. The model formulation is extended to include the consideration of the engineering staff size and the schedules of each employee to make sure that each employee does not spend more than six months every year away at the remote location and also that each employee is getting an uninterrupted 4-week vacation.
- A multi-objective decision-making framework is used. The three objective functions chosen for the optimisation aim to represent the viewpoints of the major stakeholders in the projects of SIS development and operation.

2.2. Modelling assumptions

The model presented in this subsection is largely based on the paper by Redutskiy (2017). However, considerable elaborations have been made to account for various complex proof-testing approaches.

The device failures and repairs within a MooN architecture are modelled over the period of TI. As Fig. 6 demonstrates, the Markov model for the failures and repairs includes (N – M + 2) states. State 1 stands for all N components operating properly. State 2 corresponds to one failure within the architecture. Each further state represents one more device failure. The failure of the entire redundancy architecture is represented by the last absorbing state, which corresponds to (N – M + 1) failures. Independent failures are depicted by sequential left-to-right transitions on the graph, while common cause failures are depicted by the direct transition to the absorbing state. Repairs relevant to DD and ST failures are depicted by right-to-left transitions.

Markov model equations are used for the three modelled failure types: equations (2) – (6) are expressed for DU failures in a redundancy architecture, and equations (7) for DD and ST failures.

For the DU failures, ordinary differential equations (ODE) (2) describe the probability of the subsystem being in a particular Markov model state. The non-zero transition rates are provided in (3). The stochastic process starts in state 1 when t = 0. Further course of the stochastic process is described by the switching Markov model with the time horizon

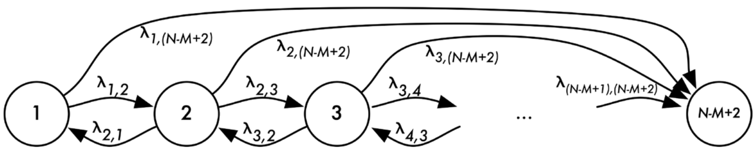

Fig. 6. Markov process of failures and repairs in a subsystem with a MooN architecture

Source: based on Redutskiy (2017).

Tab. 2. Notations used for the subsystem modelling

Notation	Description
Indices and Parameters	
i, j	indices of the Markov model states
k	index for the devices, $k \in \{1..N\}$
N	total number of components in a MooN redundancy architecture
M	necessary number of operating devices in a MooN architecture
TI	test interval, [h]
T^{test}	time required for testing and repairing one component in the architecture, [h]
λ	dangerous failure rate for one component, [h^{-1}]
λ^S	spurious trip rate for one component, [h^{-1}]
μ	repair rate, [h^{-1}]
ε	diagnostic coverage, fraction
β	common cause failure factor, fraction
$\lambda_{i,j}^{DU}$	transition rates for the model of dangerous undetected failures, [h^{-1}]
$\lambda_{i,j}^{DD}$	transition rates for the model of dangerous detected failures, [h^{-1}]
$\lambda_{i,j}^{ST}$	transition rates for the model of spurious trips, [h^{-1}]
Variables	
t	time, [h]
$p_j^{DU}(t)$	probability of (j – 1) dangerous undetected failures
$p_j^{DD}(t)$	probability of (j – 1) dangerous detected failures
$p_j^{ST}(t)$	probability of (j – 1) spurious trips in a subsystem
p_i^k	initial probability of the model's i^{th} state after testing k devices (for sequential or staggered policies)
Outputs of the Model	
λ^{DU}	dangerous undetected failure rate for a subsystem, [h^{-1}]
λ^{DD}	dangerous undetected failure rate for a subsystem, [h^{-1}]
λ^{ST}	spurious tripping rate for a subsystem, [h^{-1}]

$$\frac{dp_j^{DU}(t)}{dt} = \sum_{i=1}^{N-M+2} p_i^{DU}(t) \cdot \lambda_{i,j}^{DU} \quad j \in \{1, \dots, (N-M+2)\} \tag{2}$$

$$\begin{aligned} \lambda_{i,i}^{DU} &= -\lambda \cdot (1-\epsilon) \cdot [(N-i+1)\cdot(1-\beta)+\beta] \\ \lambda_{i,i+1}^{DU} &= \lambda \cdot (1-\epsilon) \cdot (N-i+1) \cdot (1-\beta) \\ \lambda_{i,N-M+2}^{DU} &= \lambda \cdot (1-\epsilon) \cdot \beta,\ i \in \{1, \dots, (N-M+2)\} \end{aligned} \tag{3}$$

$$p_1^{DU}(0) = 1,\ p_i^{DU}(0) = 0, i \in \{2, \dots, (N-M+2)\} \tag{4}$$

$$\begin{gathered} \pi_1^1 = 1,\ \pi_i^1 = 0, i \in \{2, \dots, (N-M+2)\}. \\ \pi_1^k = p_1^{DU}\left((k-1)\cdot T^{test}\right) + \frac{1}{N}\cdot p_2^{DU}\left((k-1)\cdot T^{test}\right), \dots, \\ \pi_{N-M+1}^k = \frac{1}{N}\cdot p_{N-M+1}^{DU}\left((k-1)\cdot T^{test}\right) + \frac{N-M+1}{N}\cdot p_{N-M+2}^{DU}\left((k-1)\cdot T^{test}\right), \\ \pi_{N-M+2}^k = 0,\ k \in \{2, \dots, N\}. \end{gathered} \tag{5}$$

$$\begin{gathered} \pi_1^1 = 1,\ \pi_i^1 = 0, i \in \{2, \dots, (N-M+2)\}. \\ \pi_1^k = p_1^{DU}\left(\frac{(k-1)\cdot TI}{2\cdot N}\right) + \frac{1}{N}\cdot p_2^{DU}\left(\frac{(k-1)\cdot TI}{2\cdot N}\right), \dots, \\ \pi_{N-M+1}^k = \frac{1}{N}\cdot p_{N-M+1}^{DU}\left(\frac{(k-1)\cdot TI}{2\cdot N}\right) + \frac{N-M+1}{N}\cdot p_{N-M+2}^{DU}\left(\frac{(k-1)\cdot TI}{2\cdot N}\right), \\ \pi_{N-M+2}^k = 0,\ k \in \{2, \dots, N\} \end{gathered} \tag{6}$$

$$\begin{aligned} \frac{dp_j^{DD}(t)}{dt} &= \sum_{i=1}^{N-M+2} p_i^{DD}(t) \cdot \lambda_{i,j}^{DD} \quad j \in \{1, \dots, (N-M+2)\} \\ \frac{dp_j^{ST}(t)}{dt} &= \sum_{i=1}^{N-M+2} p_i^{ST}(t) \cdot \lambda_{i,j}^{ST} \quad j \in \{1, \dots, (N-M+2)\} \end{aligned} \tag{7}$$

$$\begin{gathered} \lambda^{DU} = -\frac{\log\left(1-p_{N-M+2}^{DU}(TI)\right)}{TI},\ \lambda^{DD} = -\frac{\log\left(1-p_{N-M+2}^{DD}(TI)\right)}{TI}, \\ \lambda^{ST} = -\frac{\log\left(1-p_{N-M+2}^{ST}(TI)\right)}{TI} \end{gathered} \tag{8}$$

depicted in Fig. 3. The initial probabilities for the intervals of this time horizon are defined in (4), (5), and (6) for the parallel, sequential, and staggered tests respectively.

The choice of the proof testing policy has an impact on how the Markov model for the DU failures is run, as shown in equations (2) – (6). This is due to the fact that the point of proof testing is to deal specifically with the DU failures in a system. The Markov model for the DD and ST failure modes is virtually unaffected by the proof testing policy choice. Refer to the paper by Redutskiy (2017) for the full mathematical formulation of the DD and ST failures in a MooN architecture.

By producing the solutions to the ODEs (2) and (7), the failure rate values for the entire MooN architecture are obtained in (8). These values are further used in the lifecycle model of the SIS as the aggregated reliability characteristics of the subsystems.

2.3. Lifecycle modelling from the safety perspective

The lifecycle model presented next is mostly adopted from the paper by Redutskiy (2017). For the SIS subsystem, the following possible states are considered:

- performing properly,
- under the overhaul after the dangerous detected failure of the entire subsystem,
- under overhaul after a spurious trip,
- in the dangerous undetected failure mode.

For the technology, the following states are considered:

- up and running, and no incidents have occurred,
- shutdown due to a detected incident,
- shutdown due to repairs in the SIS,
- running while an incident has occurred without a proper response from the SIS (failure-on-demand state).

Given these possibilities for the SIS states and the technological unit, the entire process may be described by the states listed in Table 3 and the transitions depicted in Fig. 7. This description is, however, relevant only to safety systems that comprise exactly one sensor subsystem, one controller subsystem, and exactly one actuator subsystem. To account for realistic SIS structures (as depicted in Fig. 2d), this general model has to be adjusted.

States 1 and 2 and the last absorbing state will always be present in the model of the stochastic process. The groups of states 3–5, 6–8, and 9–11, which currently comprise three states each (corresponding to the three subsystems), will have to be expanded to the necessary number of subsystems in a real-life SIS.

The lifecycle is split into K periods, which correspond to the defined test interval and the frequency of technological overhauls. It is reflected in expression (9). Fig. 8 demonstrates an example of the time horizon. The choice of the overhaul period (OP) is related to the choice of the testing policy. If a parallel testing policy is chosen for any subsystem, then the technology has to be shut down every TI. For the case of sequential and staggered testing policies chosen for the entire SIS, the choice of OP is independent of TI. After the proof testing is finished, there is a predefined start-up time which is required to get the technology running again. It is reflected in (9).

The ODEs for the lifecycle model are provided in (10). The solution of these ODEs is used to evaluate the two safety indicators: the average probability of

Tab. 3. Markov model for the lifecycle

State	Sensors	PLCs	Actuators	Technology	Comment
1	up	up	up	running	normal course of the process
2	up	up	up	shutdown	safety function performed
3	O/S	up	up	shutdown	overhaul after a spurious trip
4	up	O/S	up	shutdown	
5	up	up	O/S	shutdown	
6	O/D	up	up	shutdown	overhaul after a dangerous detected failure
7	up	O/D	up	shutdown	
8	up	up	O/D	shutdown	
9	failure	up	up	running	undetected failure has occurred
10	up	failure	up	running	
11	up	up	failure	running	
12	SIS is down, incident has occurred				failure on demand state

Source: Redutskiy (2017).

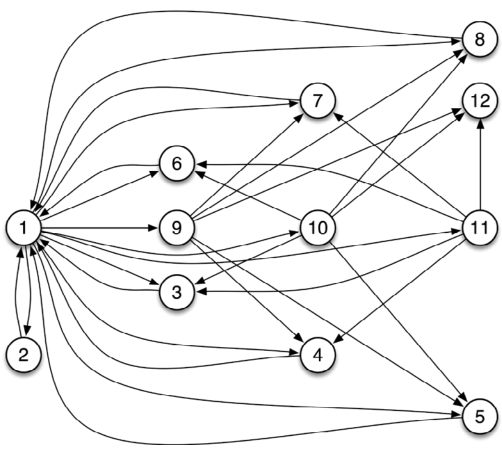

Fig. 7. Markov model of the lifecycle

Source: based on Redutskiy (2017).

Tab. 4. Notations used for the subsystem modelling

Notation	Description
Indices and Parameters	
i, j	indices of the Markov model states
q	index of the subsystems
K	total number of periods the lifecycle is split into
TI	test interval, [h]
OP	overhaul period, which has to be a multiple of *TI*, [h]
LC_h	duration of the lifecycle, [h]
T^{SU}	start-up time for the technology after the shutdown, [h]
$\lambda_{i,j}$	transition rate from state *i* to state *j*, [h^{-1}]
Variables	
$p_j(t)$	probability of the process being in the j^{th} state
Outputs of the Model	
PFD_{avg}	average probability of failure on demand
DT	expected downtime of the process, [h]

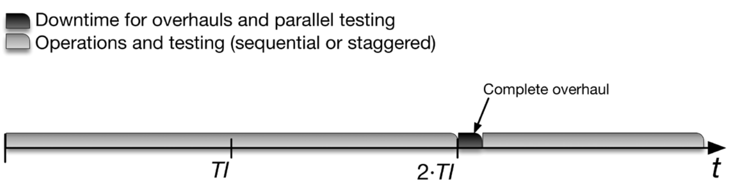

Fig. 8. An example of the time horizon for the lifecycle model where the overhaul period equals 2·*TI*

$$K = \left\lceil \frac{LC_h}{TI} \right\rceil .$$
$$t \in [0, OP] \cup [OP + T^{SU}; 2 \cdot OP] \cup \ldots \cup [(K-1) \cdot OP + T^{SU}; K \cdot OP] \tag{9}$$

$$\frac{dp_j(t)}{dt} = \sum_{i=1}^{12} p_i(t) \cdot \lambda_{i,j} \quad j \in \{1, \ldots, 12\},$$
$$p_1(0) = 1, p_2(0) = 0, \ldots p_{12}(0) = 0. \tag{10}$$

$$PFD_{avg} = \frac{1}{LC_h} \cdot \int_0^{LC_h} PFD(t)dt = \frac{1}{TI} \cdot \int_0^{OP} p_{12}(t)dt + \sum_{k=2}^{K} \frac{1}{OP - T^{SU}} \cdot \int_{(k-1)\cdot OP + T^{SU}}^{k \cdot OP} p_{12}(t)dt ,$$
$$DT = \sum_{j=2}^{2} \left[\int_0^{TI} p_j(t)dt + \sum_{k=2}^{K} \int_{(k-1)\cdot TI + T^{OD}}^{k\cdot TI} p_{12}(t)dt \right] \tag{11}$$

failure on demand and the expected facility downtime are expressed in (11).

2.4. Employee scheduling model

The blocks of the decision-making framework (Fig. 5) that are relevant to workforce organisation are, first of all, the computation of the weekly demand for the employees during a period of one year, and second, the employee scheduling problem. The latter is based on the set-covering model proposed by Dantzig (1954). As already mentioned, the requirements for facility maintenance are strict in the oil and gas industry; therefore, the demand for maintenance personnel must be met precisely. Table 5 contains the notations necessary to describe this modelling block.

The maintenance personnel requirements are determined for the two kinds of maintenance considered in this research: continuous and periodic. The number of workers required at the facility for conducting continuous maintenance is calculated based on the maximum allowable amount of time for resolving the detected device failures, which are demonstrated in (12). Personnel requirements for the

Tab. 5. Notations for the employee scheduling model

Notation	Description
Indices and Sets	
w	index of weeks in a one-year period: w ∈ {1..52}
q	index for subsystems of the SIS: transmitters, controllers, and final elements
r	index for redundancy alternatives
l	index for trips
s	index for daily schedule alternatives: 8-hour daily work or 12-hour daily schedule
f	index for maintenance workers w ∈ {1..N^{staff}}
p	index for proof testing policies: p={1,2,3} corresponding to parallel, sequential, and staggered policies
S_q^{red}	set of redundancy architecture alternatives for subsystem q
S^{trip}	set of trips (all possible trips' start times and durations of one, two, four, or six weeks)
$S^{4w.trip}$	set of all possible 4-week trips
S^{sched}	set of alternative daily work schedules (work-rest schedule during each day)
Parameters	
$N_{r,q}$	the total number of devices in subsystem q given the redundancy option r
T_q^{repair}	repair time of the devices in subsystem q
$T^{repair.max}$	the upper bound on the repair time for the entire SIS for continuous maintenance (8 hours)
$\sigma_{l,w}$	a binary parameter indicating whether week w is covered by the trip option l or not
S_s^{crew}	crew size associated with any particular daily work schedule alternative s
β_s^{sched}	employees pay rate cost modifier given the chosen daily schedule alternative s
$x_{q,p}^{TP}$	binary indicator: equals 1 if testing policy p is chosen for subsystem q
$d_w^{continuous}$	weekly demand for the employees for continuous maintenance
$d_w^{periodic}$	weekly demand for the employees for periodic parallel or sequential proof tests
$d_w^{staggered}$	weekly demand for the employees for periodic staggered proof tests for subsystem q
d_w^{emp}	total demand for the workers whose presence is required at the facility during week w
$C^{WF.est}$	initial investments associated with establishing a local workforce
$C^{WF.oper}$	yearly operational expenditures associated with the local workforce
C^{start}	subsidiary start-up cost
C^{train}	cost of training one maintenance engineer
C^{comp}	yearly expenditures associated with running the local subsidiary
C^{wage}	average salary of one maintenance engineer
d_l^{trip}	cost of one worker's trip to the remote location and back, depending on the trip duration
N^{staff}	total number of employees on the maintenance staff
Decision Variables	
$x_{f,l,s}^{emp}$	binary variable: equals 1, if employee f is taking trip l to travel to the facility and work according to daily schedule s
$y_{l,s}^{travel}$	integer variable: number of service crews taking trip l to travel to the facility and work according to daily schedule s

parallel or sequential proof tests are determined given each subsystem's architecture and the maintenance policy choice (13).

When it comes to determining the number of people required for the staggered tests, it has to be determined separately for each subsystem because of the different subsystems' architectures and, therefore, different planning periods for the staggered proof-testing approach (14). Finally, expression (15) sums up all the demand for the required number of employees. This array is further used in the employee scheduling model.

The employee scheduling block of the modelling framework proposed in this research considers the lifecycle cost as one of the objectives for decision-making. As a part of the lifecycle cost, expression (16) demonstrates the initial investments into the workforce organisation, i.e., starting up a local subsidiary and training the locally hired workforce. Further, expression (17) describes the yearly costs associated with running the company, paying salaries to the employees, and organising the schedules of employees travelling to the remotely-located industrial facilities.

$$d_w^{continuous} = \left| \sum_q \left(\sum_{r \epsilon S_q^{red}} N_{r,q} \cdot x_{r,q}^{red} - \sum_{r \epsilon S_q^{red}} M_{r,q} \cdot x_{r,q}^{red} \right) \cdot \frac{T_q^{repair}}{T^{repair.max}} \right|, \quad w = \{1, \ldots ,52\} \setminus \left\{ \frac{TI}{7 \cdot 24}; \frac{2 \cdot TI}{7 \cdot 24}; \frac{3 \cdot TI}{7 \cdot 24}; \ldots ; 52 \right\} \tag{12}$$

$$d_w^{periodic} = \sum_q \left(x_{q,1}^{TP} \cdot \sum_{r \epsilon S_q^{red}} N_{r,q} \cdot x_{r,q}^{red} + x_{q,2}^{TP} \cdot 1 \right), \quad w = \left\{ \frac{TI}{7 \cdot 24}; \frac{2 \cdot TI}{7 \cdot 24}; \frac{3 \cdot TI}{7 \cdot 24}; \ldots ; 52 \right\}. \tag{13}$$

$$d_{w,q}^{staggeredTP} = x_{q,3}^{TP} \cdot 1, \quad w = \left\{ \frac{TI}{7 \cdot 24 \cdot \sum_{r \epsilon S_q^{red}} N_{r,q} \cdot x_{r,q}^{red}} \cdot \frac{1}{2}; \frac{TI}{7 \cdot 24 \cdot \sum_{r \epsilon S_q^{red}} N_{r,q} \cdot x_{r,q}^{red}} \cdot \frac{3}{2}; \ldots ; 52 \right\}, \forall q. \tag{14}$$

$$d_w^{emp} = d_w^{continuous} + d_w^{periodic} + \sum_q d_{w,q}^{staggeredTP}, \ \forall w \tag{15}$$

$$C^{WF.est} = C^{start} + C^{train} \cdot N^{staff} \tag{16}$$

$$C^{WF.oper} = C^{comp} + 12 \cdot C^{wage} \cdot N^{staff} + \sum_{l \in S^{trips}} \sum_{s \in S^{sched}} C_l^{trip} \cdot \beta_s^{sched} \cdot S_s^{crew} \cdot y_{l,s}^{travel} \tag{17}$$

$$\sum_{l \in S^{trips}} \sum_{s \in S^{sched}} \sigma_{l,w} \cdot y_{l,s}^{travel} \geq d_w^{emp}, \ \forall w \in \{1, \ldots ,52\} \tag{18}$$

$$\sum_{f=1}^{N^{staff}} x_{f,l,s}^{emp} = S_s^{crew} \cdot y_{l,s}^{travel}, \ \forall l \in S^{trips}, \forall s \in S^{sched} \tag{19}$$

$$\sum_{s \in S^{sched}} \sigma_{l,w} \cdot x_{f,l,s}^{emp} \leq 1, \ \forall l \in S^{trips}, \forall f \in \{1, \ldots , N^{staff}\}, \forall w \in \{1, \ldots ,52\} \tag{20}$$

$$\sum_{l \in S^{trips}} \sigma_{l,w} \cdot x_{f,l,s}^{emp} \leq 1, \ \forall s \in S^{sched}, \forall f \in \{1, \ldots , N^{staff}\}, \forall w \in \{1, \ldots ,52\} \tag{21}$$

$$\sum_{l \in S^{trips}} \sum_{s \in S^{sched}} \sum_{w=1}^{52} \sigma_{l,w} \cdot x_{f,l,s}^{emp} \leq \frac{52}{2}, \ \forall f \in \{1, \ldots , N^{staff}\} \tag{22}$$

$$\sum_{l \in S^{4w.trips}} \left(1 - x_{f,l,s}^{emp}\right) \geq 1, \ \forall s \in S^{sched}, \forall f \in \{1, \ldots , N^{staff}\} \tag{23}$$

Further, the constraints for the employee scheduling model are defined. First of all, constraint (18) based on Dantzig's problem formulation ensures that the demand for the employees is covered throughout the entire planning horizon, which in our case is every week of any given year. Constraint (19) connects the integer variable from the set-covering constraint (18) with the binary variable of each employee's personal schedule. Constraints (20) and (21) ensure that each employee is assigned to no more than one trip and one daily schedule. Constraint (22) declares that each employee should not spend more than six months out of a year on trips to remote locations. And finally, constraint (23) declares that each employee has to have a four-week uninterrupted vacation.

2.5. Lifecycle modelling from the economic perspective

As suggested in IEC 61508, the economic perspective on risk reduction needs to be addressed. At the same time, lifecycle cost minimisation is one of the three priorities of the decision-making framework (Fig. 5). The present value of the total cost is evaluated for the designed solution in (24).

This evaluation includes three main components: procurement, operation and risk costs. The reader can address (Torres-Echeverria, 2009; Goble, 2010; Redutskiy, 2017) for the details of this model.

To integrate the employee scheduling model into this decision-making framework, the expenditures

$$C^{lifecycle} = C^{procurement} + \sum_{\tau=1}^{LC} \left(C_\tau^{operations} + C_\tau^{risk} \right) \cdot \frac{1}{(1+\delta)^{\tau-1}} \tag{24}$$

calculated in (16) and (17) become the components of the procurement and operating costs, respectively.

3. Computational experiment

3.1. Experiment setting and the optimisation algorithm

The suggested framework is applied to a case provided by a petroleum company operating a remotely-located facility: an oil terminal with a storage tank. The storage facility is used as temporary storage for crude and substandard oil and for several days in case the throughput at the oil processing facility is exceeded or if there is an emergency at the facility. Table 6 shows possible critical situations and the required shutdown measures.

Following the logic in Fig. 2c–d, the ESD system for this project has to comprise six subsystems to function as described in Table 6. Therefore, the developed Markov model for this solution's lifecycle comprises 21 states.

Table 6 also shows the instrumentation alternatives considered by the engineering contractor for this project. The table provides relevant characteristics of the devices, their costs, reasonable redundancy options, as well as some additional parameters for this engineering solution.

Given this study's focus on maintenance organisation, the data regarding typical trips, schedules, and compensations have been collected. Table 6 shows the

Tab. 6. Modelling parameters and equipment database

Critical process parameters				Shutdown actions		
#	Parameter	Event	Frequency, [y^{-1}]	#	Final control element	Action
1	Liquid level in the tank	Level ≥ HH	0.075	1	Safety Valve 1 on the fill line	close
2	Fire in the storage tank	Fire detected	0.03	2	Safety Valve 2 on the output line	close
				3	Pump delivering crude hydrocarbons to the tank	shutdown

Instrumentation alternatives

	Level transmitter					Fire detector			PLC			Safety valve			Pump drive	
Alternative	LT1	LT2	LT3	LT4	LT5	FD1	FD2	FD3	PLC1	PLC2	PLC3	SV1	SV2	SV3	PD1	PD2
Vendor	V1	V1	V2	V3	V3	V4	V4	V5	V6	V1	V3	V7	V1	V8	V3	V1
Failure rate, $\times 10^{-6}$ [h^{-1}]																
Dangerous failures	2	0.58	20	3	7.1	20	6	1.2	0.9	1.3	5.9	67	40	90	27	17
Spurious trips	1	4	15	1.2	3	10	4	2.28	0.8	1.1	5.5	33	33	30	13	9
Diagnostic coverage [%]	67	40	67	70	50	0	35	40	90	98	97	20	30	10	20	30
Costs																
Purchase [CU[a]]	1400	1750	850	1100	1250	40	57.5	85	22500	12500	7500	1300	1750	1400	750	1250
Design [CU]	5	5	6	5	8.5	5	5	5	2000	1000	600	650	900	900	100	100
Consumption [CU/y]	1.5	0.5	1	0.5	3	0.5	0.5	0.5	500	500	400	250	200	100	50	75
Repair [CU/event]	5	2.5	2	2.5	6	2	2	2	5	5	5	45	40	25	50	40
Test [CU/event]	5	4	5	6	8	3	3	3	1000	1000	750	500	500	500	75	100
Redundancy alternatives	1oo1, 1oo2, 1oo3, 1oo4, 2oo2, 2oo3					2oo2, 2oo3, 2oo4, 2oo5, 2oo6, 2oo7, 2oo8			1oo1, 1oo2, 1oo3, 1oo4, 2oo3			1oo1, 1oo2, 1oo3, 1oo4			1oo1, 1oo2, 1oo3	

Other parameters
CCF factor for standard circuits: β=0.035. CCF factor for electrical separation: β=0.02. Repair rate for the subsystems: $\mu=0.125\ h^{-1}$. Facility restoration rate: $\mu^{t}=0.0625\ h^{-1}$. Cost of hazard: 5 000 000 CU Lifecycle: 15 y. TI is chosen from a set of values from 12 to 52 weeks. [a] Here, fictional currency units (CU) are used to mask the real purchase costs for the devices so that particular instrumentation vendors would not be identifiable.

Trips and daily schedules with associated costs			
#	Work/rest	# of workers for continuous service	Pay rate, CU/day
1	8h/16h	3	125
2	12h/12h	2	250

Daily work schedule alternatives		
#	Duration	Pay rate cost modifier
1	1-week trip	1
2	2-week trip	1.25
3	4-week trip	1.5
4	6-week trip	2

trip alternatives with the corresponding costs, given how the case company rewards the workers for longer trips and working hours.

A script function has been developed in MATLAB to realise the decision-making framework (Fig. 5), and MATLAB's multi-objective genetic algorithm (a variant of NSGA-II, solver gamultiobj) has been used to run the black-box optimisation. For the details of this meta-heuristic algorithm, Mathworks refers the users to Deb (2001). The example at hand includes 142 decision variables, of which 140 are binaries, and the remaining two are integers. The following settings for the solver are applied: population size: 300; initial population created with the uniform distribution applying a customised function suggested by Mathworks; selection function: tournament; generational gap: 0.8 (or 80 %); crossover and mutation functions: customised functions suggested by Mathworks.

3.2. Results and discussion

Among the solutions produced as the result of the solver run, those fulfilling the SIL3 requirement are demonstrated in Table 7 and further analysed.

- The decision-making framework chooses field devices (sensors and actuators) with better reliability characteristics despite their higher costs. It is observed by comparing the chosen instrumentation to the database of the available alternatives.
- Electric separation is preferred over the baseline solution. For most subsystems in most solutions, the additional electric separation is chosen to mitigate the CCF effect despite the associated additional costs. This shows that the expected long-term production losses due to the downtime caused by CCFs are considered more costly by the decision-making framework than the investments into this safety measure.
- Electric separation is always chosen for the subsystems of PLCs and fire detectors. For the PLCs, preventing common-cause failures is critical. For the fire detector, the additional cost related to electrical separation is quite small.
- For the level sensors, device models LT4 and LT5 are chosen. Both device models are produced by the same manufacturer (V3). Based on this result, it may be suggested that when level sensors are selected, one requirement may be that they are produced by this manufacturer (V3). From the solutions, one may observe that higher redundancy architecture 1oo4 is most often chosen for LT5, while architecture 1oo3 is preferred for LT4.
- The highest redundancy among the alternatives (2oo8) is chosen for the subsystem of fire detectors. These high redundancies may be attributed to the cheap cost of fire detectors in comparison to the other devices in the SIS.
- For the subsystem of PLCs, device model PLC2 (manufacturer V1) is always chosen with the architecture 1oo3. From the instrumentation database, this controller model appears to be a trade-off between reliability and cost: reliability characteristics for PLC2 are almost as good as the best among all the alternatives, while its price is reasonable.
- For the actuator subsystems, the valve SV2 and pump drive PD2 are chosen, both produced by the same manufacturer, V1. Architecture 1oo3 is chosen most often. However, some actuator subsystems are assigned 1oo2 redundancy. Choosing the appropriate architecture for actuators should perhaps be considered in greater detail during the detailed design phase.
- For three solutions, a test interval of 12 weeks is chosen, while the overhaul period is 24 weeks (almost six months). For the remaining four solutions, a TI of 16 weeks is chosen, while the OP is 48 weeks (almost a year). For the former three solutions, one may observe that the expected downtime is no less than 142 hours, while for the remaining four solutions, the value of downtime is estimated as no more than 100 hours. When the overhaul is conducted, the system needs to shut down, which is the reason why the downtime is significantly higher for the three solutions with an OP of 24 weeks. For the company strongly focusing on reducing facility downtime, such solutions may appear suboptimal.
- Given the values of PFDavg presented in Table 7, one may observe that all the solutions achieved the required SIL3. The table also reflects the cost associated with these solutions. The lifecycle cost of the solutions is estimated at around 32 million currency units (CU). However, there is still a difference between the solution costs within the range of approximately 30-34 million units. Such a difference in costs is a matter for the stakeholders to consider while the requirements are formulated and the stakeholder's concerns are addressed.
- From the cost structure presented in Table 7, one may observe that workforce-related costs constitute at least 40 % of the overall lifecycle cost. This

fact, again, shows the importance of proper workforce planning.

- As it is possible to observe from Table 7, the costs associated with the risk is small compared to the other cost. This is achieved by the considerably strict requirements applied to the safety systems design in this research. The relatively small risk costs show that considerable risk reduction has been successfully achieved for the planned solution.
- Besides the workforce costs, another considerable component of the operational expenditures is the production losses due to the facility downtime. This cost component accounts for 25–30 % of the cost of operations.
- For the majority of solutions and for most subsystems, the sequential testing policy has been chosen, as displayed in Table 7. This result may be attributed, first of all, to the fact that sequential proof testing does not require an operational shutdown. Parallel testing requires the process shutdown, so the parallel testing policy is never chosen to avoid more downtime. Another reason why the sequential testing policy is generally preferred (even over the staggered policy, which also does not require operations shutdown) is that this decision-making problem combines maintenance planning with its implementation through employee scheduling. Because of it, the optimisation algorithm tries to organise the maintenance in such a way that during the course of operations, there is a rather stable demand for the number of employees to be constantly present at the facility (which in this case is either 3 or 4 crews for various solutions), and only for the periods of major overhauls, more workers are required (in this example, six crews).
- A closer look at the employee scheduling results reveals that for the normal course of operations, generally, four-week trips with an 8-hour daily working schedule (i.e., crew size of three workers) are preferred. For the weeks when the overhauls are conducted, one-week trips with a 12-hour daily schedule (crew size of two) are preferred.
- A comparison of the produced results with earlier results presented in the paper by Redutskiy et al. (2021) reveals that it was possible to achieve an approx. 15 % reduction in workforce-related costs through a more detailed consideration of the employee scheduling aspects. The solutions presented in Table 7 demonstrate that with this approach, the algorithm is inclined to choose somewhat more elaborate architectures, which

Tab. 7. Optimisation results

Choices of instrumentation and maintenance									
#	Level sensor	Fire detector	PLC	Safety valve 1	Safety valve 2	Pump drive	TI, w	Overhaul period, w	Staff size
1	1oo4 / e / LT5 sequential	2oo8 / e / FD3 sequential	1oo3 / e / PLC2 sequential	1oo3 / e / SV2 sequential	1oo2 / e / SV2 staggered	1oo3 / e / PD2 sequential	12	24	19
2	1oo4 / b / LT4 sequential	2oo8 / e / FD3 sequential	1oo3 / e / PLC2 sequential	1oo2 / e / SV2 sequential	1oo3 / e / SV2 sequential	1oo3 / e / PD2 sequential	12	24	19
3	1oo3 / e / LT4 sequential	2oo6 / e / FD3 sequential	1oo3 / e / PLC2 sequential	1oo3 / b / SV3 staggered	1oo2 / e / SV2 sequential	1oo2 / e / PD2 sequential	16	48	19
4	1oo4 / e / LT5 sequential	2oo8 / e / FD3 sequential	1oo3 / e / PLC2 sequential	1oo3 / e / SV2 sequential	1oo3 / e / SV2 staggered	1oo3 / e / PD2 staggered	16	48	20
5	1oo3 / e / LT4 sequential	2oo6 / e / FD3 sequential	1oo3 / e / PLC2 sequential	1oo3 / e / SV3 sequential	1oo3 / e / SV2 sequential	1oo3 / e / PD2 sequential	16	48	20
6	1oo4 / e / LT5 sequential	2oo8 / e / FD3 sequential	1oo3 / e / PLC2 sequential	1oo3 / e / SV2 sequential	1oo2 / e / SV2 sequential	1oo2 / e / PD2 sequential	16	48	21
7	1oo4 / e / LT5 sequential	2oo6 / e / FD3 sequential	1oo3 / e / PLC2 sequential	1oo2 / e / SV2 staggered	1oo3 / e / SV2 staggered	1oo3 / e / PD2 staggered	12	24	23

Reliability characteristics and cost structure for the Pareto-front solutions							
#	PDF_{avg}	DT, h	Lifecycle cost, CU	Procurement cost, CU	Cost of operations, CU	Workforce-related costs, CU	Risk costs, CU
1	$2.6208 \cdot 10^{-05}$	142	32 362 339	11 721 650	20 636 203	13 113 790	4 486
2	$2.7351 \cdot 10^{-05}$	143	32 339 055	11 701 730	20 632 643	13 113 790	4 682
3	$3.7958 \cdot 10^{-05}$	98	29 775 209	11 219 360	18 549 351	13 636 924	6 498
4	$3.0243 \cdot 10^{-05}$	97	34 219 297	11 795 778	22 418 341	16 391 556	5 177
5	$3.7958 \cdot 10^{-05}$	98	29 775 209	11 219 360	18 549 351	13 636 924	6 498
6	$2.9056 \cdot 10^{-05}$	96	34 252 125	11 824 353	22 422 799	16 391 556	4 974
7	$2.6208 \cdot 10^{-05}$	142	32 362 339	11 721 650	20 636 203	13 113 790	4 486

results in approx. 15 % higher procurement costs; however, when it comes to the total cost of the solution's lifecycle, a reduction of approx. 3–8 % is observed compared to earlier research which has not accounted for many workforce organisation details.

Conclusions

The paper focuses on the design and maintenance of an ESD system and organising the workforce to maintain this system at a remotely-located hazardous industrial facility. This research shows the benefits of combining the aspects of design, maintenance, and workforce planning into one decision-making framework.

This research has demonstrated the possibility of incorporating complex maintenance policies into a Markov model, an aspect that has not been explored well in the literature. It allowed the optimisation algorithm to choose between the proof tests, which require temporarily shutting down the operations and the policies that can be implemented while the facility is continuously running. In the oil and gas sector, the losses associated with production downtime are significant; therefore, the latter options of testing policies are chosen.

This research has elaborated the employee scheduling model by considering the travel schedule for every employee on the staff, allowing for the introduction of such aspects as the maximum time an employee spends at a remote location annually, as well as ensuring the mandatory continuous vacation period. This allows for a more precise evaluation of the staff size in comparison to standard set-covering formulation when the number of crews taking a certain trip is determined, and the maintenance is planned through the collective notion of the effort of the entire staff.

In addition, this research has focused on each individual employee's travel schedule. This measure allows getting a more accurate size of the crew and limiting the amount of time spent on the remote location to ensure a continuous annual vacation availability for each employee.

The main area for applying the analysis and results produced in this research is developing comprehensive requirements for the safety systems, which should lay the groundwork for the detailed engineering design. Therefore, the obtained results and deduced recommendations correspond to the strategic planning level of an engineering project. From the analysis of the results produced by the developed decision-making framework, the following recommendations have been concluded:

- advisable device models and/or instrumentation manufacturers for particular subsystems.
- advisable redundancies and separation decisions for the SIS subsystems
- advisable maintenance strategy: proof testing frequency and maintenance policy.

In real-life engineering practice, the requirements for safety systems can be vague: in most cases, the documentation merely states that the developed solution has to achieve SIL3. The obtained results may help to shape straightforward recommendations that can be utilised in the requirement specification document.

The main limitation of this research is that the conclusions obtained from the modelling and optimisation results are suitable only for each particular problem context to which they apply. In other words, it is not possible to use the same conclusions for every engineering project or for planning any kind of facility. For example, although PLCs and actuators supplied by vendor V1 were preferred in this case, these device models will not necessarily be chosen for another project case. Nevertheless, the developed approach has proven that at least some conclusions can be drawn for every particular project. Therefore, an insight into strategic SIS planning may be gained.

This research focuses on planning only one SIS among the several automated systems deployed at any real-life hazardous industrial facility. One obvious direction for future research is to extend the decision-making to several SISs and plan the workforce requirements and schedules for the entire facility and for all the automated systems at the facility. Another direction for future research is to apply employee scheduling on the tactical or operative level of decision-making by incorporating more details from the practical perspective of workforce organisation.

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Investigating cause-and-effect relationships between supply chain 4.0 technologies

Hojatallah Sharifpour Yaser Ghaseminezhad
Mohammad Hashemi-Tabatabaei Maghsoud Amiri

ABSTRACT

The developments of the fourth industrial revolution have caused changes in all areas of society, including production. The changes in production caused by the fourth industrial revolution have also resulted in fundamental changes in the supply chain and have converted it to supply chain 4.0. Organisations must be receptive to supply chain 4.0 to maintain their competitive advantage. Therefore, this study aimed to investigate the relationships among supply chain 4.0 technologies so that, by learning and understanding these connections, industries can pave the way for the implementation of these technologies in their supply chains and use them in problem-solving. The literature review was used to identify the supply chain 4.0 technologies, and the Delphi technique was applied to extract them, including the Internet of Things (IoT), cyber-physical systems, cloud computing, big data, blockchain, artificial intelligence, Radio-frequency Identification (RFID), augmented reality, virtual reality, and simulation. The relationships of supply chain 4.0 technologies were examined using the DEMATEL technique and based on interpretive structural modelling (ISM), their deployment map was drawn. The type of technologies was determined using the MICMAC method. The MICMAC analysis found that the artificial intelligence technology is independent and, based on the findings through the DEMATEL technique, this technology is related to simulation, which belongs to the first level of the interpretive structural modelling technique, and IoT, cloud computing, big data, and blockchain technologies, which are at the second level. Based on the ISM method, RFID, virtual reality, augmented reality and simulation technologies are located at the first level; IoT, cyber-physical systems, cloud computing, big data and blockchain technologies are situated in the second level; and artificial intelligence technology belongs to the third level. According to the related literature, few studies have been conducted on the issues of supply chain 4.0 and the technologies that affect it.

KEY WORDS

supply chain management (SCM), supply chain 4.0, Industry 4.0, DEMATEL, ISM, MICMAC

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Mohammad Hashemi-Tabatabaei

Allameh Tabataba'i University, Iran
ORCID 0000-0002-2185-6102

Corresponding author:
e-mail: M.H.Tabatabaei@atu.ac.ir

Hojatallah Sharifpour

University of Mazandaran, Iran
ORCID 0000-0003-2219-0362

Yaser Ghaseminezhad

University of Imam Hossein, Iran
ORCID 0000-0003-0294-2096

Maghsoud Amiri

Allameh Tabataba'i University, Iran
ORCID 0000-0002-0650-2584

Introduction

The supply chain is vital to the organisation as it must provide the facilities needed to meet critical processes and procurement requirements (Sobb, Turnbull & Moustafa, 2020). The supply chain is a type of pull production that processes in response to customer requests and consists of all stakeholders, including customers, suppliers, manufacturers, transportation, warehouse workers, etc. To keep its competitive advantage, the supply chain must adapt to

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changes in technology and customer needs and requirements (Ramirez-Peña et al., 2020).

With the advent of the Fourth Industrial Revolution, to achieve or maintain a competitive advantage, the supply chain must achieve advanced technological changes to meet the expectations of its stakeholders. The Fourth Industrial Revolution restructured all supply chain processes from the supply of raw materials to the production line and the last stage when the product reaches the end customer. Under these circumstances, the supply chain is digitised and renewed with more advanced technological equipment (Kaya, Paksoy & Garza-Reyes, 2020).

The Fourth Industrial Revolution, or Industry 4.0, was introduced in 2011 in Hannover, Germany. The strategy of Industry 4.0 has directly affected the competitive global market and is also a natural source of value creation (Frederico, 2021a). The biggest goal of Industry 4.0 is to develop an automated production system in which different machines in a factory can communicate with each other, detect environmental conditions (heat, humidity, energy, weather, etc.) and identify the needs of the system through analysing the collected data (Kaya, Paksoy & Garza-Reyes, 2020). Industry 4.0 changes in production have also affected the supply chain because it is inseparable from production.

With the advent of Industry 4.0 systems, the term "supply chain 4.0" was coined, which expressly signifies the Fourth Industrial Revolution and the integration of intelligent systems into supply chain systems. Supply chain 4.0 is known for the physical and technological integration of systems across the network, which enables increased productivity, organisation, and profitability. It is identified with actions independent from location, prevalent integration, various automated services, and its ability to respond to customer needs and requirements (Sobb, Turnbull & Moustafa, 2020). Supply chain 4.0 drivers are mainly big data and the IoT, under which complementary technologies such as Radio-frequency identification (RFID), sensors, Global Positioning System (GPS), Electronic Data Interchange (EDI), and data sensing equipment can be easily tracked throughout supply chain activities (Kaya, Paksoy & Garza-Reyes, 2020).

Based on the literature review, a limited number of studies have been conducted on supply chain 4.0 and the technologies that affect it. In research with a systematic literature review and content analysis on the issues of knowledge management and supply chain 4.0, Sartori et al. (2021) proposed a conceptual model for knowledge management in the area of supply chain 4.0. Liu & Chiu (2021) investigated the relationships between supply chain digitisation and firm performance using the PLS-SEM method. Kaya et al. (2020) investigated the impact of Industry 4.0 on the supply chain and the role of the IoT and big data in the supply chain industry. Sobb et al. (2020) studied military supply chains 4.0 and explored their unique differences from commercial supply chains. Ramirez-Peña et al. (2020) investigated the relationships among supply chain 4.0 sustainability in the aerospace, shipbuilding and automotive sectors. In their research results, it was found that the lack of identification of supply chain 4.0 technologies has caused the lack of understanding of supply chain 4.0 by industries. Therefore, to fill this gap, this study first identified these technologies and then investigated the relationships among them.

According to the studies described in the supply chain literature, supply chains are currently ineffective and lack transparency. Creating a supply chain and maintaining its effective management is complicated, which affects not only the profits of companies and manufacturers but also the final price of the product. Therefore, under these circumstances, most supply and distribution networks face problems with managing all these components together. Many of the problems of current supply chains can be solved by applying and implementing supply chain 4.0 technologies because supply chain 4.0, by relying on its ability, offers excellent and innovative ways to maintain competitive advantage and better supply chain management. Therefore, this study aimed to investigate the relationships among supply chain 4.0 technologies using DEMATEL and ISM methods so that by learning and understanding these relationships, the industries can implement the technologies in their supply chains and solve related problems.

This study focused on supply chain 4.0 technologies to increase the productivity of industries and reduce or eliminate the major problems of the traditional supply chain. The next sections of this paper discuss the theoretical foundations, the methodology, conclusions, discussion, and, finally, present conclusions.

1. Literature review

1.1. Supply chain 4.0

A supply chain is a network of systems, processes, and organisations that produce valuable goods and services and deliver them to the end user. Supply chains are the links between nations, physical distribution networks, and transportation systems, forming a global network. Supply chains include flows of materials, goods, and information that passes within and through the organisations. They are linked by a range of tangible and intangible facilitators, including relationships, processes, activities, and integrated information systems. Their essential technologies are transport systems, communication platforms and networks, and physical distribution networks (Sobb, Turnbull & Moustafa, 2020; Kozma, 2017).

The supply chain has undergone fundamental changes with the advent of the fourth industrial revolution or the so-called industry 4.0. Industry 4.0 combines advanced manufacturing techniques and Information Technologies (IT) to create intelligent systems. Industry 4.0 is building Intelligent Manufacturing Systems (IMS) by changing modes of operation, design, product service, and manufacturing systems. This is a new technological and forward-looking perspective aimed at increasing the effectiveness and efficiency of the whole industry chain. Industry 4.0 is based on the advent of new technologies, including Additive Manufacturing, cloud computing, the Internet of Things (IoT), Cyber-Physical Systems (CPS), and big data systems. These technologies can provide operations control and enable real-time adaptability and flexibility based on demands. They also allow the production of small and customised batches of production. The main advantages of these technologies are the creation of intelligent systems that provide better energy efficiency at the factory level and thus have positive environmental impacts (Nara et al., 2021). The changes that the Industry 4.0 technologies have made to the supply chain have led to fundamental changes in the supply chain and the advent of a new form of the supply chain, known as the fourth-generation supply chain or supply chain 4.0.

Supply Chain 4.0 is defined as a set of related activities linked to each other through the coordination, planning, and control of products and services to suppliers and consumers. It aims to find new ways to create added value for customers and suppliers and generate more revenue through the integration and coordination of forecasting, ownership, production, distribution, sales, and marketing processes (Martins, Simon & Campos, 2020). Supply chain 4.0 is the integration of communication and production technologies that enhance the production of traditional supply chain systems through location-independent actions, routine integration, various automated services, and its ability to respond to customer needs and requirements. Fig. 1 shows the dependence of a supply chain in the Industry 4.0 context, which indicates the integration of customers, suppliers, tools, factories, and engineering to get connected through the physical supply network (Sobb, Turnbull & Moustafa, 2020).

Having additive manufacturing technologies, automation, industrial robots, augmented reality, cyber security, blockchain, the Internet of Data — people and services —, semantic technologies, simu-

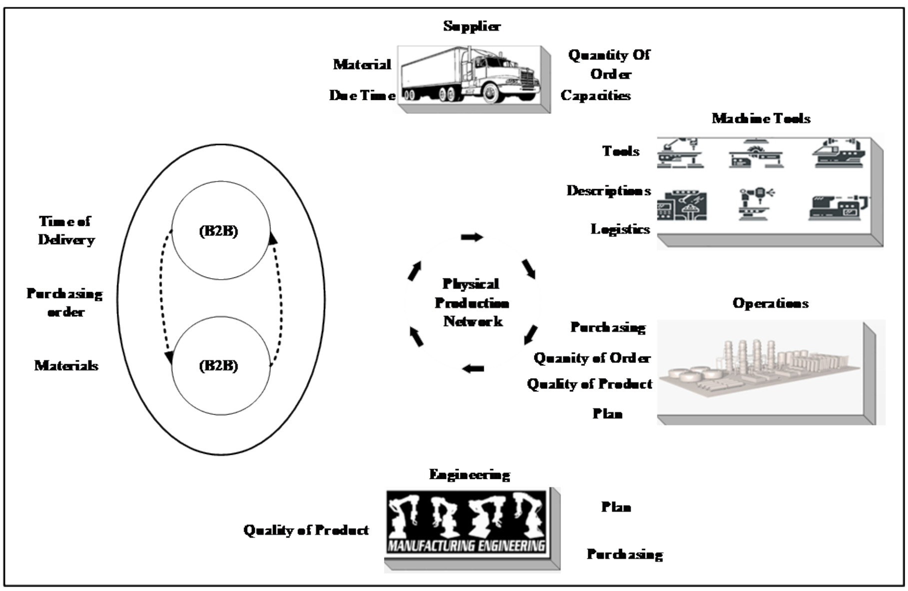

Fig. 1. Conceptual architecture of supply chain 4.0
Source: Sobb, Turnbull & Moustafa, 2020.

lation, and modelling in the context of Industry 4.0, the whole supply chain (not only customers and suppliers but also their assets, products, and operating environment) can be integrated. More data can be generated with excellent quality and higher speed. In addition, these technologies allow organisations to increase flexibility, productivity, reliability, and accountability in their operations. Also, by allowing real-time reorganisation of entire processes, organisations can reduce the effect of Bullwhip and the costs associated with supply chain operations (Martins, Simon & Campos, 2020).

1.2. Technologies affecting the supply chain 4.0

1.2.1. Internet of Things (IoT)

IoT is a network of physical and virtual objects with embedded technology described as a means to communicate, identify, or interact with internal states or the external environment. The Internet of Things contains an ecosystem that includes objects, communications, applications, and data analytics in which each object is identifiable. The IoT is used in industrial processing, agriculture, logistics, product lifecycle management, medicine, healthcare, smart home/building, public safety, environmental monitoring, intelligent mobility, and intelligent tourism (Rueda-Rueda & Portocarrero, 2021). Fig. 2 shows the communications in the context of IoT.

With the digitalisation of supply chain processes, such technologies as IoT are becoming increasingly important for organisations interested in embracing and applying Industry 4.0 developments. IoT is closely related to energy management in factories, logistics, transportation, and the creation of smart business models. IoT is becoming increasingly important in terms of the need to realise real-time information as well as the need to improve after-sale services through sensors existing inside its products, which are based on big data technology; because its performance, defects and consumption patterns are provided for the customer (Ramirez-Peña et al., 2020).

IoT in the supply chain is defined as a network of physical objects that digitally shares the supply chain interactions among multiple organisations, enables agility, visibility, and information sharing, and facilitates planning, controlling, and coordinating supply chain processes (Rejeb et al., 2020). Abdel-basset, Manogaran and Mohamed (2018) used the IoT to create an intelligent and secure supply chain management system by providing a website for suppliers. On this website, managers and suppliers get complete information about the whole supply chain, which has made the supply chain transparent. Mostafa, Hamdy and Alawady (2019) presented a new approach to the Internet of Things in warehouse management. In this approach, by connecting to several objects through collecting real-time data, IoT enables sharing of real-time data. The resulting information can then be used to support automated decision-making. Sharma, Kaur and Singh (2020) proved that the IoT provides real-time storage conditions in warehousing and supply chain management of pharmaceutical products

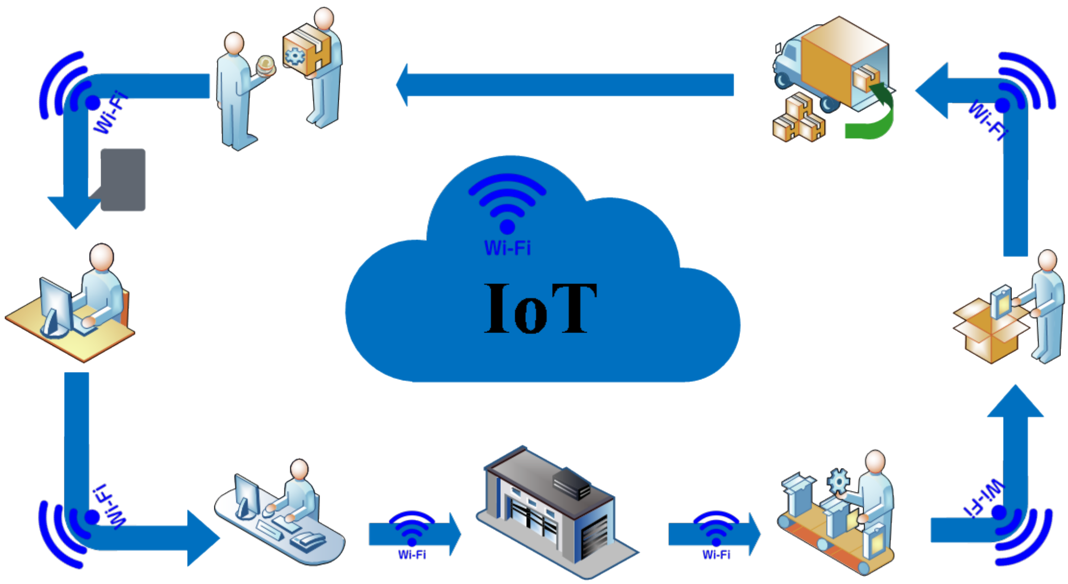

Fig. 2. Communications in the context of IoT

and improves visibility to increase operational efficiency. Al-Rakhami and Al-Mashari (2021) created a trust model in the supply chain with IoT elements. The trust model makes the supply chain more efficient, simplifies data sharing, and reduces computational storage and latency requirements while increasing the security of IoT-based supply chain management.

1.2.2. Cyber-physical systems (CPS)

Cyber-physical systems include machines, storage systems, and manufacturing facilities that are digitally developed and provide integration based on information and communication technologies (ICT). Cyber-physical systems are characterised by decentralisation, adaptation, and autonomous behaviour. Cyber-physical systems also offer supply chain opportunities for real-time monitoring of production conditions and logistics activities while enabling prognosis, diagnosis, and remote control (Martins, Simon & Campos, 2020). Cyber-physical systems are often combined with data collection and monitoring control systems. Moreover, cyber-physical systems can be used in several areas of the supply chain, especially in the production space. These systems can potentially change how people interact with supply chain products and processes and potentially improve service levels' performance and flexibility (Sobb, Turnbull & Moustafa, 2020). Chen, Dui and Zhang (2020) studied supply chain resilience using cyber-physical systems. Wang and Zhang (2020) investigated the use of cyber-physical systems to identify defects in supply chain management.

1.2.3. Cloud computing

The basis of cloud computing expanded in the 1980s with the advent of the Internet. Cloud computing is currently one of the best computing paradigms of information technology. This is due to the advances in existing computational models that include parallel computing, network computing, distributed computing, and other computational paradigms. This technological strategy allows consumers to introduce their communications to a system of computing resources where users can quickly increase or decrease their demands with minimal interaction from third parties (Alam, 2020). Elements of cloud computing include computing, analytics, networking, and storage; these elements are identified in service categories as software services, platforms, networks, and infrastructures. In general, the benefits of cloud computing include flexibility, location independence, scalability, and cost-effectiveness (Sobb, Turnbull & Moustafa, 2020). The cloud computing concept is shown in Fig. 3.

Singh et al. (2015) proposed an integrated system using cloud computing technology in which all stakeholders of the beef supply chain can minimise and measure carbon dioxide emissions with reasonable costs and infrastructure. Schniederjans, Ozpolat and

Fig. 3. A view of cloud computing

Chen (2016) proved that cloud computing technology has a positive and significant effect on cooperation between humanitarian organisations and their suppliers, which causes a substantial increase in the agility of humanitarian organisations. Suherman and Simatupang (2017), using cloud computing technology, proposed a business network model that integrates such systems as ERP in the supply chain and creates an overall perspective in the supply chain, which includes buying, distributing, and viewing inventory. Li, Sun and Wu (2019) used cloud computing technology to improve the logistics distribution planning of coastal ports. Lu et al. (2021) conducted a study in which they addressed reducing the risks of the financing supply chain using cloud computing.

1.2.4. Big data

Big data is the generic term for large, defined or undefined giant data. An unimaginable massive amount of data is generated daily in various sectors such as health, management, social networks, marketing, finance, etc. Since this collected data is nothing but a vast amount of data, it is essential to interpret it to be analysed quickly. Previously, businesses did not prefer to keep their data in archives for long periods and did not analyse their data set. However, with new technological advances, data can be examined, stored, and made available in a secure environment (Kaya, Paksoy & Garza-Reyes, 2020). The importance of big data has been acknowledged because of the significant challenge that factories face in processing large amounts of information. These intelligent systems can monitor and control supply chain processes and also provide information about the breakdowns for the entire planning system and production control, and ultimately offer helpful solutions to employees (Ramirez-Peña et al., 2020).

Lamba and Singh (2017) investigated big data in operations and supply chains and optimised them. Researchers also found that big data can facilitate setting up, procuring, and selecting suppliers. Hofmann (2017) studied the use of big data features to reduce the Bullwhip effect. Raman et al. (2018) developed a reference model of supply chain operations by combining big data and supply chain management. Kamble and Gunasekaran (2020) studied supply chain performance measures and metrics using big data.

Maheshwari, Gautam and Jaggi (2021) acknowledged that big data analysis in supply chain management, logistics management, and inventory management facilitates customer behaviour analysis, consequently optimising business operations.

1.2.5. Additive manufacturing

The basic premise of additive manufacturing technology is that a model initially generated by a computer through a 3D design system can be built directly without the need for process planning. Although this may not seem easy at first, additive manufacturing technology dramatically now simplifies the process of producing complex 3D objects from computer-aided design data. Other manufacturing strategies require careful analysis of the part geometry to determine such things as the construction order of various features, the tools and processes that must be used, and the additional equipment that might be needed to complete the part. Still, additive manufacturing only requires some basic dimensional details and little understanding of how the additive manufacturing machine works and the used materials (Gibson et al., 2021). Additive manufacturing, together with product design freedom, customisation ability, and product diversity, which are determinants of supply chain competition, play an essential role in the viability of a complex product and also help reduce wasted resources and emissions by setting up a collaborative program (Ramirez-Peña et al., 2020).

Ming-Chuan Chiu (2016) stated in his study that additive manufacturing improves lead time and total cost in supply chain performance. According to Handal (2017), additive manufacturing in the supply chain must be used when it can adopt supply chain strategies and when the product is unique and complex. Luomaranta and Martinsuo (2020) stated in their study that additive manufacturing efficiency requires innovation at the supply chain level, which includes innovations in business processes, technology, and structure. Arora et al. (2020) conducted a study to fill the gap in the supply chain localisation of a device in the medical industry through additive manufacturing. Afshari, Searcy and Jaber (2020) explored the applications of the drivers of additive manufacturing innovation in green supply chains.

1.2.6. Blockchain

Blockchain can be defined as a decentralised and distributed guide for smart contracts delivering opportunities for tracking, document management, supply chain automation, payment applications, and other business transactions. Among a network of trading partners, blockchain provides documents replicated in almost real-time among a network of trading partners and documents remain unchanged. Blockchain captures information from enterprise resource planning and distributes it available to a network of documents across different companies. The benefits of blockchain enable organisations to understand their customers better, especially their demands (Javaid et al., 2021).

Blockchain is widely used in such digital currencies as bitcoin, while blockchain technology can be applied to various systems and processes, including the supply chain. Implementing a blockchain in the supply chain increases chain security. Also, it increases the flexibility of the supply chain against cyber-attacks by identifying vulnerable or potentially exploited components in all stages of the chain (Sobb, Turnbull & Moustafa, 2020).

Francisco and Swanson (2018) studied the use of blockchain to improve transparency and traceability in the supply chain. Longo et al. (2019) used the design and development of a software interface to connect the blockchain to the organisation's systems and allow organisations to share information with their partners at different levels. They examined the accuracy, integrity, and non-manipulation of data over time through blockchain, which builds confidence in the non-manipulation of data. Moreover, the software interface presented in their study leads to the reconstruction of supply chain operations and the integration of the supply chain with the blockchain. Azzi, Chamoun and Sokhn (2019) investigated how to integrate the blockchain into supply chain architecture to create a reliable, transparent, and secure system. Rejeb and Rejeb (2020) studied supply chain sustainability through blockchain. Researchers have declared that the economic, social, and environmental aspects of the supply chain with blockchain lead to new business models without new intermediaries, higher operational efficiency, building loyal relationships between supply chain partners, and supporting humanitarian logistics. Wang, Chen and Zghari-Sales (2021) studied ways to design an active supply chain with a blockchain that leads to transparency and profitability of a blockchain-based supply chain.

1.2.7 Artificial intelligence

Artificial intelligence (AI) works to replicate some aspects of technology-based human intelligence. From a business perspective, artificial intelligence and data analytics systems allow individuals to systematise information that is usually already available in the marketplace in a segregated way and turn data into business decisions. Therefore, they consider only tools that are useful for facilitating an organisation's decision-making processes (Sestino & De Mauro, 2021). Artificial intelligence-based systems and capabilities enable them to have a high degree of self-control, and by these means, respond to situations that were not pre-planned or explicitly anticipated during their development and make independent decisions and choices of action, with little or no control of their users (Thiebes, Lins & Sunyaev, 2021).

Baryannis, Dani et al. (2019) used artificial intelligence in the field of supply chain risk management to analyse data and make decisions about potential risks. Baryannis, Validi et al. (2019) studied the use of artificial intelligence in solving problems in the risk supply chain. Modgil, Singh and Claire (2021) worked on using artificial intelligence in their study to develop the capabilities of vision, risk, sourcing, and distribution which in turn leads to the improvement of supply chain resilience. Belhadi, Mani et al. (2021) examined the maximisation of the benefits of artificial intelligence to create sustainable supply chain performance. Belhadi, Kamble et al. (2021) explored the applications of artificial intelligence, such as fuzzy logic programming and big data, in machine learning and operating systems and considered them the most promising techniques to improve resilience supply chain strategies.

1.2.8. Augmented reality

Augmented reality combines such digital components as graphics, sound, and other sensory enhancements which affect real-world video streams with real-time interaction between the user and digital elements. Although virtual reality replaces the natural world with the virtual world, augmented reality completes the user's perception of the real world in a comprehensive way without completely hiding the real world (Venkatesan et al., 2021). Augmented reality systems can play a role in logistics operations, construction, training and maintenance and help employees by combining computer-generated data and the physical world. It also helps to select logistics solutions, leading to a quick and efficient selection of products and, at the same time, reduces operating time (Demir & Paksoy, 2020). Demir, Yilmaz and Paksoy (2020) stated in their study that augmented reality in logistics allows quick access to predicted information. Bhatia (2021) showed how different stakeholders of a supply chain could use the potential of augmented reality to play their roles and perform their tasks efficiently.

1.2.9. Virtual reality

Virtual reality is an artificial environment experienced through sensory stimuli (such as sights and sounds) provided by a computer, in which one's actions partly determine what occurs in the environment. Virtual reality technology aims to immerse users in a completely artificial environment with different forms of technology to address one or more senses (Scavarelli, Arya & Teather, 2021). The virtual reality user is fully involved in an artificial environment and has no interaction with the surrounding real world. However, augmented reality allows the user to see and interact with the real world and virtual objects. Virtual reality replaces reality with an artificial environment, but augmented reality improves the real environment instead of replacing it (Demir, Yilmaz & Paksoy, 2020).

1.2.10. Simulation

Simulation is an imitation of the performance of a real-world design or process on a computer platform. Simulation makes it possible to generate the system's artificial history and view it to infer the operational characteristics of the natural system (Kaya, Paksoy & Garza-Reyes, 2020). Supply chain flexibility through simulation enables risks to be assessed before implementation, positively impacting supply chain risk management and saving many natural resources, making the supply chain more sustainable (Ramirez-Peña et al., 2020). Supply chain 4.0 technologies and their brief description can be seen in Table 1.

Tab. 1. Supply chain 4.0 technologies

Supply chain 4.0 technologies	Brief definition	Source
Internet of Things (IoT)	Connecting any physical object to the world wide web and identifying it in the virtual world	Abdel-basset et al., 2018; Al-Rakhami & Al-Mashari, 2021; Cañas et al., 2020; Kaya et al., 2020; Mostafa et al., 2019; Ramirez-Peña et al., 2020; Rejeb et al., 2020; Rueda-Rueda & Portocarrero, 2021; Sharma et al., 2020; Sobb et al., 2020; Frederico, 2021b
Cyber-Physical Systems (CPS)	Integrating all systems and subsystems and their monitoring and control	Cañas, Mula & Campuzano-Bolarín, 2020; Chen, Dui & Zhang, 2020; Kaya, Paksoy & Garza-Reyes, 2020; Martins, Simon & Campos, 2020; Ramirez-Peña et al., 2020; Sobb, Turnbull & Moustafa, 2020; Wang & Zhang, 2020; Frederico, 2021a
Cloud Computing	Calculating data and analysing, connecting and storing it in the network	Singh et al., 2015; Schniederjans, Ozpolat & Chen, 2016; Suherman & Simatupang, 2017; Li, Sun & Wu, 2019; Alam, 2020; Kaya, Paksoy & Garza-Reyes, 2020; Martins, Simon & Campos, 2020; Ramirez-Peña et al., 2020; Sobb, Turnbull & Moustafa, 2020; Lu et al., 2021
Big Data	Massive volumes of structured or unstructured data that are continuous, heterogeneous, and variable, from connecting people with mobile devices, objects, and machines to the world wide web	Hofmann, 2017; Lamba & Singh, 2017; Raman et al., 2018; Cañas, Mula & Campuzano-Bolarín, 2020; Kamble & Gunasekaran, 2020; Kaya, Paksoy & Garza-Reyes, 2020; Martins, Simon & Campos, 2020; Ramirez-Peña et al., 2020; Frederico, 2021a; Maheshwari, Gautam & Jaggi, 2021
Additive Manufacturing	Rapid prototyping process and 3D printing	Afshari et al., 2020; Arora et al., 2020; Gibson et al., 2021; Handal, 2017; L iu & Chiu, 2021; Luomaranta & Martinsuo, 2020; F. de C. Martins et al., 2020b; Ming-Chuan Chiu, 2016; Ramirez-Peña et al., 2020
Blockchain	A decentralised and distributed guide for smart contracts	Francisco & Swanson, 2018; Azzi, Chamoun & Sokhn, 2019; Longo et al., 2019; Martins, Simon & Campos, 2020; Ramirez-Peña et al., 2020; Rejeb & Rejeb, 2020; Sobb, Turnbull & Moustafa, 2020; Frederico, 2021a; Javaid et al., 2021; Wang, Chen & Zghari-Sales, 2021
Artificial intelligence	Replicating some aspects of technology-based human intelligence	Baryannis, Dani, et al., 2019; Baryannis, Validi, et al., 2019; Ramirez-Peña et al., 2020; Sobb, Turnbull & Moustafa, 2020; Belhadi, Mani, et al., 2021; Modgil, Singh & Claire, 2021; Sestino & De Mauro, 2021; Thiebes, Lins & Sunyaev, 2021

Radio-frequency identification (RFID)	A mechanism for obtaining pre-embedded information in the object label via radio frequency	Martins, Simon & Campos, 2020; Frederico, 2021a
Augmented Reality	Adding a new layer of information to the real human environment	Cañas, Mula & Campuzano-Bolarín, 2020; Demir & Paksoy, 2020; Martins, Simon & Campos, 2020; Bhatia, 2021; Liu & Chiu, 2021; Venkatesan et al., 2021
Virtual Reality	A three-dimensional environment generated to be able to produce real-world works and experiences with a high degree of precision	Demir, Yilmaz & Paksoy, 2020; Kaya, Paksoy & Garza-Reyes, 2020; Scavarelli, Arya & Teather, 2021
Simulation	An approximate imitation of an operation, process, or system that represents its performance over time	Kaya, Paksoy & Garza-Reyes, 2020; Martins, Simon & Campos, 2020; Ramirez-Peña et al., 2020; Frederico, 2021a

1.3. Related studies on supply chain 4.0

The literature review found that few studies have been done on implementing supply chain 4.0 in industries, and most of these studies only addressed the supply chain 4.0 literature. None of these studies addressed the relationships and rankings of supply chain 4.0 technologies and mostly referred to the application of Industry 4.0 technologies in the supply chain. Some of the research efforts on supply chain 4.0 are discussed next.

Frederico (2021a) conducted a study that aimed to present the concept of the supply chain in the Industry 5.0 phenomenon. His study, "From Supply Chain 4.0 to Supply Chain 5.0: Findings from a Systematic Literature Review and Research Directions", used a systematic literature review method. The findings indicate a substantial gap related to Industry 5.0 approaches in the supply chain area. The researcher also acknowledged that industry strategy, innovation and technology, society and sustainability, and transition issues are the foundations of Industry 5.0 and noted that the leadership of organisations, policymakers and other stakeholders that are involved in the supply chain, and mainly users that currently work with Industry 4.0 plans, can benefit from this research with clear guidance on the dimensions required for structural design and implementation of the Industry 5.0 strategy.

Sartori, Frederico and de Fátima Nunes Silva (2021) conducted a study, "Organizational knowledge management in the context of supply chain 4.0: A systematic literature review and conceptual model proposal", aimed at a systematic literature review and content analysis of knowledge management and supply chain 4.0. The researchers proposed a conceptual model for knowledge management in the field of supply chain 4.0. Also, the researchers found that Industry 4.0 made significant changes in supply chain management and knowledge management.

Liu and Chiu (2021) investigated the relationships between supply chain digitisation, supply chain integration and a firm's performance. In their study, "Supply Chain 4.0: the impact of supply chain digitalisation and integration on firm performance", the researchers used an online survey of Chinese employees in the supply chain industry and found that both digitisation and supply chain integration have a positive effect on the firm's performance. The researchers also acknowledged that supply chain digitisation positively moderates the relationship between supply chain integration and the firm's performance.

Kaya, Paksoy and Garza-Reyes (2020) conducted a study to explore how Industry 4.0 affects the supply chain and investigate the role of the Internet of Things and big data in the supply chain industry. Researchers in their study found that the Internet of Things (IoT) is used in the entire process from supplier to material handling, material transportation, and production to product delivery to customers. Moreover, IoT can also optimise the processes of the transportation management system, and the potential use of IoT technology is enormous across the supply chain. The researchers acknowledged that the IoT-enabled supply chain could be visualised as an intelligent, interconnected network that physically connects the levels of many suppliers, manufacturers, service providers, distributors, and customers in different parts of the world.

Cañas, Mula and Campuzano-Bolarín (2020) explored the current knowledge of supply chain 4.0 with a sustainability approach. Reviewing the literature, the researchers considered the three main dimensions of sustainability, namely economic, social and environmental. They found that more attention has been paid to the environmental dimension in Industry 4.0, while less attention has been given to the social dimension. The researchers also acknowledged that reference frameworks were identified along with Industry 4.0 models, algorithms, heuris-

Tab. 2. Summary of related research on supply chain 4.0

Authors	Title	Aims	Type/Approach
Frederico, 2021a	From Supply Chain 4.0 to Supply Chain 5.0: Findings from a Systematic Literature Review and Research Directions	Proposing a conceptual model for knowledge management in the field of supply chain 4.0	literature review
Sartori et al., 2021	Organisational knowledge management in the context of supply chain 4.0: A systematic literature review and conceptual model proposal	Investigating the relationships between supply chain digitisation, supply chain integration and firm performance	PLS-SEM
Liu & Chiu, 2021	Supply Chain 4.0: the impact of supply chain digitalisation and integration on firm performance	Providing a conceptual framework for project management in Supply Chains 4.0	literature review
Kaya et al., 2020	The Impact of the Internet of Things on Supply Chain 4.0	Investigating the way Industry 4.0 affects the supply chain and the role of the Internet of Things and big data in the supply chain industry	literature review
Cañas et al., 2020	A General Outline of a Sustainable Supply Chain 4.0	Investigating the current knowledge of the supply chain 4.0 with a sustainability approach	literature review
Sobb et al., 2020	Supply Chain 4.0: A Survey of Cyber Security Challenges, Solutions and Future Directions	Investigating the military supply chains 4.0 and their unique differences from commercial supply chain	literature review
Ramirez-Peña et al., 2020	Sustainability in the Aerospace, Naval, and Automotive Supply Chain 4.0: Descriptive Review	Investigating the relationship between supply chain 4.0 sustainability in the aerospace, shipbuilding and automotive sectors	literature review

tics, metaheuristics, and technologies, which enable sustainability in supply chains.

Sobb, Turnbull and Moustafa (2020) investigated the military supply chains 4.0 and their unique differences from the commercial supply chains. They also explored their strengths, weaknesses, dependencies, and the fundamental technologies on which they are built. According to the findings of their study, the technologies that underpin supply chain 4.0 include blockchain, smart contracts, artificial intelligence applications, cyber-physical systems, and the industrial Internet of Things. The researchers acknowledged that each of these technologies, individually and in combination, creates cyber security issues that must be addressed.

Ramirez-Peña et al. (2020) investigated the relationship between supply chain 4.0 sustainability in the aerospace, shipbuilding, and automotive sectors. They found that lean methods are common in three areas and different technologies focus on sustainability. The researchers acknowledged that the automotive industry is one of the industries that can be very useful to the other two sectors through collaborative programmes and help them the most. As a result, the automotive sector benefits from the consequent applicable advantages. The researchers also declared that the aerospace and shipbuilding sectors do not do much work to promote a sustainable culture in supply chain management or to include training programmes for their personnel on issues related to Industry 4.0.

Table 2. shows the summary of the literature review on related research.

2. Research methods

Improving supply chain performance is one of the Multi-Criteria Decision-Making (MCDM) issues. To improve supply chain performance, various evaluation criteria must be considered. Therefore, it is appropriate to use existing methods in multi-criteria issues to improve supply chain performance. In the present study, two methods of literature review and field study have been used. The literature review was collected by reviewing the studies that were accessible via the Internet. The methodology of the study is shown in Fig. 4.

The literature review found that the fourth-generation supply chain has been considered in universities and science centres and has not been thoughtfully implemented in the industry, and this has led to a lack of industry awareness in this area. Therefore, experts of the present study were selected from university professors who had mastered supply chain 4.0.

This study aims to investigate supply chain 4.0 technologies and analyse the cause-and-effect relationships between them. To achieve this goal, supply chain 4.0 technologies were first identified in the research literature. In the next step, to select the critical factors in the study area, questionnaires based on the Delphi method were distributed among the experts and the factors with the mean higher than seven were selected. According to previous studies, the threshold limit of seven was considered because it leads to a better correlation among the data (Lewis, 1993). After selecting the final most influential elements, various techniques were used to determine the relationships. According to the studies that were conducted, Decision Making Trial and Evaluation (DEMATEL) technique is one of the best techniques in this regard in terms of analysing relationships and also determining the importance of factors. For this reason, this technique was used in the present study. DEMATEL is a valuable method for the analysis of cause-and-effect relationships, where it can provide quantitative measures and consider the relevant structural model. Also, this method can effectively structure a relationship map for each criterion with clear interrelationships between sub-criteria. It can also be used to create causal diagrams that can visualise the cause-and-effect relationships of subsystems. The Interpretive Structural Modelling (ISM) technique was also used to rank the supply chain 4.0 technologies. The ISM is also a pioneer in terms of being understandable to a wide range of users, as well as being a tool for integrating the different perceptions of experts compared to other methods, and it is also applicable in studying complex and diverse systems.

2.1. DEMATEL technique

The DEMATEL technique was first introduced by Gabus and Fontela (1972) to solve real-world problems. The DEMATEL technique is an effective way to analyse direct and indirect relationships between system components according to their type and intensity (Wu & Chang, 2015). Analysing the general relationship between the components in the DEMATEL technique allows for obtaining a better understanding of structural relationships, as well as an ideal way to solve complex system problems. Next, the steps of the DEMATEL technique are discussed (Dwijendra et al., 2021).

Step 1: A four-level comparative scale for measuring the relationship between criteria with the help of expert opinions is required after collecting the desired criteria. These four scales that are used to

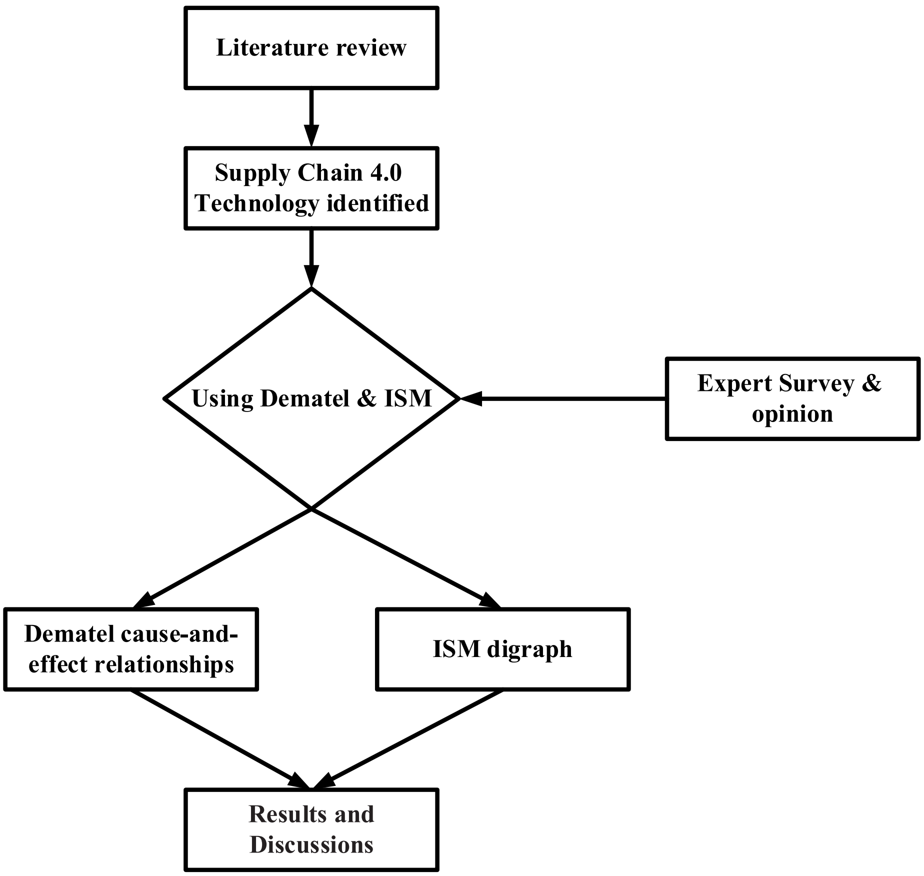

Fig. 4. Methodology of the study

describe the relationship between the criteria are, respectively, 0 (No impact), 1 (Low impact), 2 (Equal impact), 3 (High impact), and 4 (Very high impact). The next step is to get expert opinions regarding pairwise comparisons. The result of this step is displayed using the D Matrix and its components with aij. Each member represents the degree of influence that criteria i has on criteria j.

Step 2: Equations 1 and 2 can be used to convert the matrix of direct relations (D) into the normalised matrix of direct relations.

Step 3: Once the normalised matrix (X) is formed, the total relation matrix (T) is received from Equation 3, in which I is the identity matrix.

Step 4: The causal diagram is drawn based on the total relation matrix. To do so, the sum of the elements in the rows and columns of the matrix T are named r and c and are calculated using Equations 4 and 5. Then, the horizontal axis of the diagram is calculated by adding r and c (r + c), which is called the significance axis. The vertical axis of the diagram, which is called the dependency axis, is obtained by subtracting r and c (r-c). In general, if (r-c) is positive, the criterion belongs to the cause group; otherwise, it belongs to the effect group. Therefore, a causal diagram is obtained through points with coordinates r + c and r-c.

2.2. Interpretative Structural Modelling Technique

Interpretative Structural Modelling Technique was first proposed by Warfield (1973) to analyse complex socioeconomic systems. This technique helps people to show the complexity of knowledge in the field of study as a model of interaction to increase their understanding. The steps of the interpretative structural modelling technique are as follows (Chauhan et al., 2018):

Step 1: List the desired criteria or elements.

Step 2: Use the criteria that were identified in the first step and define a content relationship between them according to each pair of criteria.

Step 3: Form the Structural Self-Interaction Matrix (SSIM): experts perform pairwise comparisons between the two criteria i and j based on four symbols:

V: If criterion i only affects criterion j.

A: If criterion j only affects criterion i.

X: If criterion i affects criterion j, criterion j also affects criterion i.

O: If there is no relationship between criterion i and criterion j.

Step 4: Form the initial reachability matrix: the SSIM is formed using pairwise comparisons based on the four symbols of V, A, X and O. This structural matrix is then converted to a zero-one matrix called the initial reachability matrix. In this matrix, only the numbers 0 and 1 exist, and the rule is to place the numbers 0 and 1 instead of the four symbols to show the kind of relationship between the two criteria i and j as follows:

- If the intersection of the criteria (i, j) in the structural self-interaction matrix is V, in the initial reachability matrix, the element (i, j) is 1, and the element (j, i) is 0.
- If the intersection of the criteria (i, j) in the structural self-interaction matrix is A, in the initial reachability matrix, the element (i, j) is 0, and the element (j, i) is 1.
- If the intersection of the criteria (i, j) in the structural self-interaction matrix is X, in the initial reachability matrix, the element (i, j) and the element (j, i) are 1.
- If the intersection of the criteria (i, j) in the structural self-interaction matrix is O, in the initial reachability matrix, the element (i, j) and the element (j, i) are 0.

Step 5: Form the final reachability matrix: After the formation of the initial reachability matrix, the

$$X = D.S \tag{1}$$

$$s = max\left(max_{1 \le i \le n} \sum_{j=1}^{n} a_{ij}\ ,\ max_{1 \le j \le n} \sum_{i=1}^{n} a_{ij}\right),\ i.j = 1,2,\ldots,n \tag{2}$$

$$T = X(I - X)^{-1} \qquad When\ \lim_{m \to \infty} X^m = [0]_{n \times n} \tag{3}$$

$$r = (r_i)_{n \times 1} = \left(\sum_{j=1}^{n} t_{ij}\right)_{n \times 1} \tag{4}$$

$$c = (c_j)_{1 \times n} = \left(\sum_{i=1}^{n} t_{ij}\right)_{1 \times n} \tag{5}$$

final reachability matrix is formed using the criteria that are obtained by considering the transgression relationship. Transgression means that if criterion "a" is related to criterion "b" and criterion "b" is related to criterion "c", then criterion "a" is also related to criterion "c". It should be noted that in the final reachability matrix, the entries obtained through the transgression relations are shown as 1. After the formation of the final reachability matrix, this matrix is added to the unit matrix and called the final reachability matrix.

Step 6: Level the final reachability matrix: After forming the final reachability matrix, the criteria are levelled by determining the reachability set and antecedent set for each of the criteria and determining the common set. The reachability set of each variable contains the criteria that lead to or affect that variable. In other words, for the criteria that number 1 is placed in their variable column, the reachability set comes in a column. Conversely, it shows the antecedent set of criteria that are affected by a variable or a system component. The commonality of the two sets of reachability and antecedent, a common set, is an intersection. Criteria with the common set the same as the antecedent set have the first priority level. By eliminating these criteria and repeating this process for other criteria, the levels of other criteria are also determined. After levelling the final reachability matrix, draw the ISM diagram.

Step 7: Analyse the classification of criteria, using diving power and dependence: to classify criteria in the final reachability matrix, influence and dependency must be calculated for each element. The penetrating power of a component or criterion is the number of criteria affected by the relevant criterion, including the criterion itself. The dependency power is the number of criteria that affect the relevant criterion and lead to its achievement. These penetrating and dependency powers are used in the cross-impact matrix multiplication applied to classification (MICMAC), in which the criteria are divided into four groups: autonomous, dependent, linkage, and independent criteria. Autonomous criteria have weak influence and dependence. These criteria are relatively separate from the system and, in fact, have little link or connection to other elements of the system, although their relationship might be substantial. Dependent criteria have low penetrating power but high dependency power. Linking criteria have strong linkage, strong influence, and strong dependency. These criteria are unstable because any action on these criteria will affect other criteria or feedback to them. Independent criteria have high penetrating power with low dependency power.

3. Research results

As mentioned before, the expert population of the present study included five academic-industrial experts who are fully acquainted with the subject under study. First, the experts were interviewed to determine the importance of each of the fourth-generation technologies. They were analysed using the Delphi technique, and as a result, the final technologies of the supply chain 4.0 were shown in (Table 3) with their equivalent names:

After identifying the essential technologies of supply chain 4.0, the DEMATEL technique was used to determine the cause-and-effect relationships between the technologies. Therefore, the questionnaire was administered to experts, and they made pairwise comparisons based on the following scale: No impact (0), Low impact (1), Equal impact (2), High impact (3), Very high impact (4). After collecting expert responses and aggregating their opinions using the arithmetic mean, the initial reachable matrix was formed, as shown in (Table 4).

The initial relation matrix was normalised based on Equation 1 and named N. In Equation 1, (D) is the initial relation matrix and (S) is the largest number in the row and column, as shown in (Table 5). After the formation of the normalised matrix (X), we get the total relation matrix (T) from Equation 3, in which I is the identity matrix (Table 6).

Based on the total relation matrix, we draw the causal diagram. To do so, the sum of the elements in the rows and columns of the matrix T is named r and c and calculated using Equations 4 and 5. Then, the horizontal axis of the diagram is calculated by adding r and c (r + c), which is called the significance axis. The vertical axis of the diagram, which is called the dependency axis, is obtained by subtracting r and c (r-c). In general, if (r-c) is positive, the criterion belongs to the cause group; otherwise, it belongs to the effect group. Therefore, the causal diagram is obtained through points with coordinates r + c and r-c. Table 7 shows the values of r and c, and Fig. 5 shows the cause and effect of supply chain 4.0 technology.

As shown in Fig. 5, C2 (cyber-physical systems), C8 (augmented reality), and C9 (virtual reality) technologies belong to the cause group, and C1 (the Internet of Things), C3 (cloud computing), C4 (big

Tab. 3. Supply chain 4.0 technologies and their equivalent names

Supply chain 4.0 technologies	Equivalent names
Internet of Things (IoT)	C_1
Cyber-Physical Systems (CPS)	C_2
Cloud Computing	C_3
Big Data	C_4
Blockchain	C_5
Artificial intelligence	C_6
Radio-frequency identification (RFID)	C_7
Augmented Reality	C_8
Virtual Reality	C_9
Simulation	C_{10}

Tab. 4. Initial reachability matrix

D	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	Σ
C_1	0/0	3/8	4/0	3/7	4/0	3/6	3/8	2/4	3/4	2/3	31
C_2	3/6	0	2/4	2/9	3/2	4	1/3	2/3	2/4	2/7	24/8
C_3	2/4	1/3	0	3/4	3/8	2/8	1/3	1/8	2/9	3/2	22/9
C_4	3/6	2/4	3/8	0	3/9	2/8	1/7	1/2	2/3	2/7	24/4
C_5	4	2/3	1/7	2/4	0	4	3/9	1/3	1/4	2/3	23/3
C_6	3/7	1/4	3/7	3/4	2/6	0	0/8	2/2	1/3	3/6	22/7
C_7	4	2/3	1/8	1/4	2/9	1/3	0	0/8	1/4	1/2	17/1
C_8	3/8	1/8	2/3	1/8	2/4	1/3	2/8	0	3/8	4	24
C_9	3/7	2/4	1/7	3/6	3/7	2/3	1/4	3/7	0	3/8	26/3
C_{10}	2/9	0/4	1/3	2/3	1/4	3/8	0/4	3/8	4	0	20/3
Σ	31/7	18/1	22/7	24/9	27/9	25/9	17/4	19/5	22/9	25/8	

Tab. 5. Normalised matrix

X	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
C_1	0/00	0/12	0/13	0/12	0/13	0/11	0/12	0/08	0/11	0/07
C_2	0/11	0/00	0/08	0/09	0/10	0/13	0/04	0/07	0/08	0/09
C_3	0/08	0/04	0/00	0/11	0/12	0/09	0/04	0/06	0/09	0/10
C_4	0/11	0/08	0/12	0/00	0/12	0/09	0/05	0/04	0/07	0/09
C_5	0/13	0/07	0/05	0/08	0/00	0/13	0/12	0/04	0/04	0/07
C_6	0/12	0/04	0/12	0/11	0/08	0/00	0/03	0/07	0/04	0/11
C_7	0/13	0/07	0/06	0/04	0/09	0/04	0/00	0/03	0/04	0/04
C_8	0/12	0/06	0/07	0/06	0/08	0/04	0/09	0/00	0/12	0/13
C_9	0/12	0/08	0/05	0/11	0/12	0/07	0/04	0/12	0/00	0/12
C_{10}	0/09	0/01	0/04	0/07	0/04	0/12	0/01	0/12	0/13	0/00

Tab. 6. Total relation matrix

T	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
C_1	0/39	0/34	0/41	0/42	0/46	0/43	0/34	0/32	0/38	0/39
C_2	0/42	0/20	0/32	0/35	0/38	0/39	0/23	0/28	0/31	0/35
C_3	0/37	0/22	0/22	0/34	0/37	0/34	0/21	0/25	0/30	0/34
C_4	0/42	0/26	0/35	0/26	0/39	0/35	0/24	0/24	0/30	0/34
C_5	0/41	0/25	0/28	0/31	0/27	0/37	0/29	0/23	0/26	0/31
C_6	0/40	0/22	0/33	0/34	0/34	0/26	0/20	0/26	0/26	0/35
C_7	0/34	0/21	0/23	0/23	0/29	0/24	0/14	0/17	0/21	0/22
C_8	0/42	0/24	0/30	0/31	0/35	0/30	0/27	0/20	0/34	0/37
C_9	0/44	0/28	0/31	0/38	0/41	0/36	0/25	0/33	0/26	0/39
C_{10}	0/35	0/18	0/25	0/29	0/28	0/34	0/17	0/29	0/32	0/23

data), C5 (blockchain), C6 (artificial intelligence), C7 (radio-frequency identification (RFID)), and C10 (simulation) technologies belong to the effect group.

To describe the structural relationships between supply chain 4.0 technologies, a threshold value of p must be obtained from the T matrix. In the present study, the threshold is obtained through the mean of the T matrix, and its value is equal to 0.3065. (Table 8) shows the entries maintained if a variable in the T matrix is larger than the threshold, and they are considered zero if the variable is smaller than the threshold.

According to Table 8, C1 (the Internet of Things) technology has a relationship with itself, and C2 (cyber-physical systems), C3 (cloud computing), C4 (big data), C5 (blockchain), C6 (artificial intelligence), C7 (radio-frequency identification (RFID)), C8 (augmented reality), C9 (virtual reality) and C10 (simulation) technologies;

Tab. 7. Values of importance and dependent axis

	R	C	R+C	R-C
C_1	3/89	3/96	7/85	-0/07
C_2	3/22	2/4	5/62	0/82
C_3	2/96	2/98	5/94	-0/02
C_4	3/16	3/24	6/4	-0/09
C_5	2/99	3/55	6/54	-0/57
C_6	2/96	3/38	6/34	-0/42
C_7	2/3	2/34	4/63	-0/04
C_8	3/1	2/56	5/66	0/54
C_9	3/39	2/96	6/35	0/44
C_{10}	2/7	3/29	5/99	-0/59

C2 (cyber-physical systems) technology has a relationship with C1 (the Internet of Things), C3 (cloud computing), C4 (big data), C5 (blockchain), C6 (artificial intelligence), C9 (virtual reality), and C10 (simulation) technologies;

C3 (cloud computing) technology has a relationship with C1 (the Internet of Things), C4 (big data), C5 (blockchain), C6 (artificial intelligence), and C10 (simulation) technologies;

C4 (big data) technology has a relationship with C1 (the Internet of Things), C3 (cloud computing), C5 (blockchain), C6 (artificial intelligence), and C10 (simulation) technologies;

C5 (blockchain) technology has relationship with C1 (the Internet of Things), C4 (big data), C6 (artificial intelligence) and C10 (simulation) technologies;

C6 (artificial intelligence) technology has a relationship with C1 (the Internet of Things), C3 (cloud computing), C4 (big data), C5 (blockchain), and C10 (simulation) technologies;

C7 (radio-frequency identification (RFID)) technology has only a relationship with C1 (the Internet of Things) technology;

C8 (augmented reality) technology has a relationship with C1 (the Internet of Things), C4 (big data), C5 (blockchain), C9 (virtual reality), and C10 (simulation) technologies;

C9 (virtual reality) technology has a relationship with C1 (the Internet of Things), C3 (cloud computing), C4 (big data), C5 (blockchain), C6 (artificial intelligence), C8 (augmented reality), and C10 (simulation) technologies;

C10 (simulation) technology has a relationship with C1 (the Internet of Things), C6 (artificial intelligence), and C9 (virtual reality) technologies.

To draw the deployment map of supply chain 4.0 technologies, the interpretative structural modelling

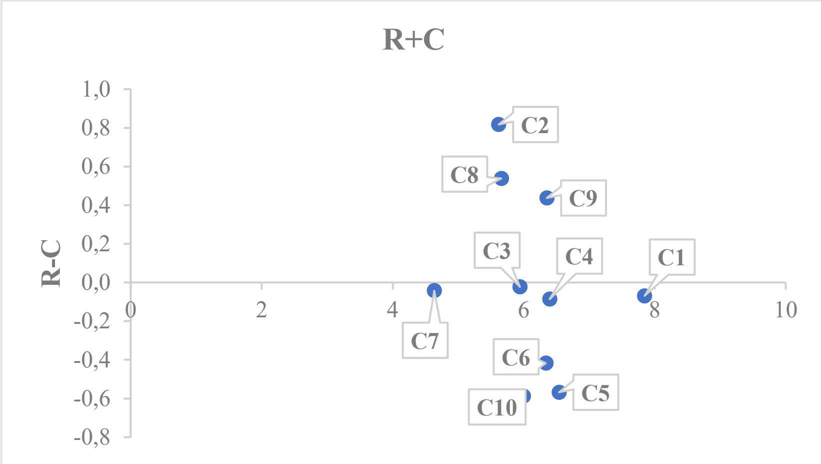

Fig. 5. Causal diagram

Tab. 8. Matrix of relationships between supply chain 4.0 technologies

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
C_1	0/39	0/34	0/41	0/42	0/46	0/43	0/34	0/32	0/38	0/39
C_2	0/42	0/00	0/32	0/35	0/38	0/39	0/00	0/00	0/31	0/35
C_3	0/37	0/00	0/00	0/34	0/37	0/34	0/00	0/00	0/00	0/34
C_4	0/42	0/00	0/35	0/00	0/39	0/35	0/00	0/00	0/00	0/34
C_5	0/41	0/00	0/00	0/31	0/00	0/37	0/00	0/00	0/00	0/31
C_6	0/40	0/00	0/33	0/34	0/34	0/00	0/00	0/00	0/00	0/35
C_7	0/34	0/00	0/00	0/00	0/00	0/00	0/00	0/00	0/00	0/00
C_8	0/42	0/00	0/00	0/31	0/35	0/00	0/00	0/00	0/34	0/37
C_9	0/44	0/00	0/31	0/38	0/41	0/36	0/00	0/33	0/00	0/39
C_{10}	0/35	0/00	0/00	0/00	0/00	0/34	0/00	0/00	0/32	0/00

Tab. 9. Structural Self-Interaction Matrix (SSIM)

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
C_1	-	X	O	O	O	O	V	O	O	O
C_2		-	O	V	X	O	O	O	V	O
C_3			-	X	A	A	O	O	O	O
C_4				-	V	O	O	V	V	O
C_5					-	O	O	O	O	O
C_6						-	O	O	O	O
C_7							-	O	O	O
C_8								-	X	X
C_9									-	X
C_{10}										-

technique has been used. To show how the relationship between the two criteria i and j was, the experts performed pairwise comparisons based on VAXO symbols. The Structural Self-Interaction Matrix and Initial reachability matrix are shown in Tables 9 and 10.

After the formation of the initial reachability matrix, the final reachability matrix is formed through the criteria that are obtained by considering transgression relation. In the final reachability matrix, the criteria obtained through the transgression relation 1 are shown as 1. Table 11 shows the final reachability matrix

After the final reachability matrix is formed, the criteria are levelled by determining the reachability set and antecedent set for each of the criteria and determining the common set. After determining the level Table 12–14, the deployment map of the supply chain 4.0 technologies is drawn in Fig. 6.

To classify supply chain 4.0 technologies in the final reachability matrix, influence and dependency must be calculated for each element. Dependence and power values are shown in Table 15. The penetrating power of a component or criterion is the number of criteria that are affected by the relevant criterion, including the criterion itself. The dependency power is the number of criteria that affect the relevant criterion and lead to its achievement. These penetrating and dependency powers are used in the cross-impact matrix multiplication applied to classification (MICMAC), in which the criteria are divided into four groups: autonomous, dependent, linkage, and independent (stimulus criterion) criteria. According to Fig. 7, C1 (the Internet of Things), C2 (cyber-physical

Tab. 10. Initial reachability matrix

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
C_1	-	1	0	0	0	0	1	0	0	0
C_2	1	-	0	1	1	0	0	0	1	0
C_3	0	0	-	1	0	0	0	0	0	0
C_4	0	0	1	-	1	0	0	1	1	0
C_5	0	1	1	0	-	0	0	0	0	0
C_6	0	0	1	0	0	-	0	0	0	0
C_7	0	0	0	0	0	0	-	0	0	0
C_8	0	0	0	0	0	0	0	-	1	1
C_9	0	0	0	0	0	0	0	1	-	1
C_{10}	0	0	0	0	0	0	0	1	1	-

Tab. 11. Final reachability matrix

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
C_1	1	1	*1*	*1*	*1*	0	1	*1*	*1*	*1*
C_2	1	1	*1*	1	1	0	*1*	*1*	1	*1*
C_3	*1*	*1*	1	1	*1*	0	*1*	*1*	*1*	*1*
C_4	*1*	*1*	1	1	*1*	0	*1*	*1*	1	*1*
C_5	*1*	1	1	*1*	1	0	*1*	*1*	*1*	*1*
C_6	*1*	*1*	1	*1*	*1*	1	*1*	*1*	*1*	*1*
C_7	0	0	0	0	0	0	1	0	0	0
C_8	0	0	0	0	0	0	0	1	1	1
C_9	0	0	0	0	0	0	0	1	1	1
C_{10}	0	0	0	0	0	0	0	1	1	1

systems), C3 (cloud computing), C4 (big data), and C5 (blockchain) are interconnected technologies, while C6 (artificial intelligence) technology is independent, and C7 (radio frequency identification (RFID)), C8 (augmented reality), C9 (virtual reality), and C10 (simulation) technologies are dependent. MICMAC analysis is shown in Fig. 7.

According to the relationships obtained from the DEMATEL technique and the levelling of the ISM, the relationships among the technologies of the supply chain 4.0 based on the levels obtained from the ISM are shown in Fig. 8. As it can be seen, the critical technology of artificial intelligence is related to the simulation technologies that are at the first level and the technologies of IoT, cloud computing, big data, and blockchain that are at the second level. Other relationships are as follows:

4. Discussion of the results

Reviewing the literature revealed the increasing number of research works in supply chain 4.0. Based on the bibliometric analysis, the term "supply chain 4.0" is used more frequently in engineering, computer science, business, and management compared to

Tab. 11. Final reachability matrix

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
C_1	1	1	*1*	*1*	*1*	0	1	*1*	*1*	*1*
C_2	1	1	*1*	1	1	0	*1*	*1*	1	*1*
C_3	*1*	*1*	1	1	*1*	0	*1*	*1*	1	*1*
C_4	*1*	*1*	1	1	*1*	0	*1*	*1*	1	*1*
C_5	*1*	1	1	*1*	1	0	*1*	*1*	*1*	*1*
C_6	*1*	*1*	1	*1*	*1*	1	*1*	*1*	*1*	*1*
C_7	0	0	0	0	0	0	1	0	0	0
C_8	0	0	0	0	0	0	0	1	1	1
C_9	0	0	0	0	0	0	0	1	1	1
C_{10}	0	0	0	0	0	0	0	1	1	1

Tab. 12. Level partition matrix

Criterion	Reachability set	Antecedent set	Intersection set	Level 1
C_1	C_1,C_2,C_3,C_5,C_6	$C_1,C_2,C_3,C_5,C_7,C_8,C_9, C_{10}$	C_1,C_2,C_3,C_5	-
C_2	C_1,C_2,C_3,C_5,C_6	$C_1,C_2,C_3,C_5,C_7,C_8,C_9, C_{10}$	C_1,C_2,C_3,C_5	-
C_3	C_1,C_2,C_3,C_5,C_6	$C_1,C_2,C_3,C_5,C_7,C_8,C_9, C_{10}$	C_1,C_2,C_3,C_5	-
C_4	C_1,C_2,C_3,C_5,C_6	$C_1,C_2,C_3,C_5,C_7,C_8,C_9, C_{10}$	C_1,C_2,C_3,C_5	-
C_5	C_1,C_2,C_3,C_5,C_6	$C_1,C_2,C_3,C_5,C_7,C_8,C_9, C_{10}$	C_1,C_2,C_3,C_5	-
C_6	C_6	$C_1,C_2,C_3,C_5, C_6, C_7,C_8,C_9, C_{10}$	C_6	-
C_7	C_1,C_2,C_3,C_5,C_6,C_7	C_7	C_7	✓
C_8	$C_1,C_2,C_3,C_5,C_6, C_8,C_9, C_{10}$	C_8,C_9, C_{10}	C_8,C_9, C_{10}	✓
C_9	$C_1,C_2,C_3,C_5,C_6, C_8,C_9, C_{10}$	C_8,C_9, C_{10}	C_8,C_9, C_{10}	✓
C_{10}	$C_1,C_2,C_3,C_5,C_6, C_8,C_9, C_{10}$	C_8,C_9, C_{10}	C_8,C_9, C_{10}	✓

Tab. 13. Continuation Level partition Level 2

Criterion	Reachability set	Antecedent set	Intersection set	Level 2
C_1	C_1,C_2,C_3,C_5,C_6	C_1,C_2,C_3,C_5	C_1,C_2,C_3,C_5	✓
C_2	C_1,C_2,C_3,C_5,C_6	C_1,C_2,C_3,C_5	C_1,C_2,C_3,C_5	✓
C_3	C_1,C_2,C_3,C_5,C_6	C_1,C_2,C_3,C_5	C_1,C_2,C_3,C_5	✓
C_4	C_1,C_2,C_3,C_5,C_6	C_1,C_2,C_3,C_5	C_1,C_2,C_3,C_5	✓
C_5	C_1,C_2,C_3,C_5,C_6	C_1,C_2,C_3,C_5	C_1,C_2,C_3,C_5	✓
C_6	C_6	C_1,C_2,C_3,C_5, C_6	C_6	-

Tab. 14. Continuation Level partition Level 3

Criterion	Reachability set	Antecedent set	Intersection set	Level 3
C_6	C_6	C_1,C_2,C_3,C_5, C_6	C_6	✓

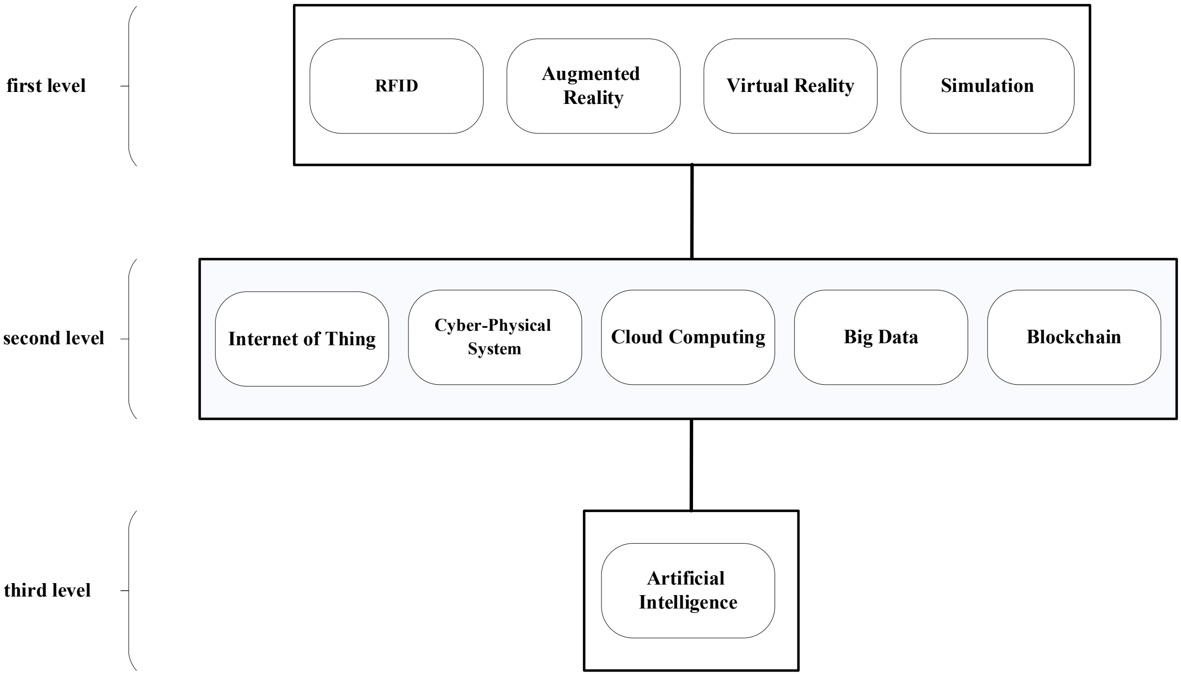

Fig. 6. Deployment map of supply chain 4.0 technologies

Tab. 15. Dependence and power values

	Power	Dependence
C_1	6	9
C_2	6	9
C_3	6	9
C_4	6	9
C_5	6	9
C_6	1	10
C_7	7	1
C_8	9	3
C_9	9	3
C_{10}	9	3

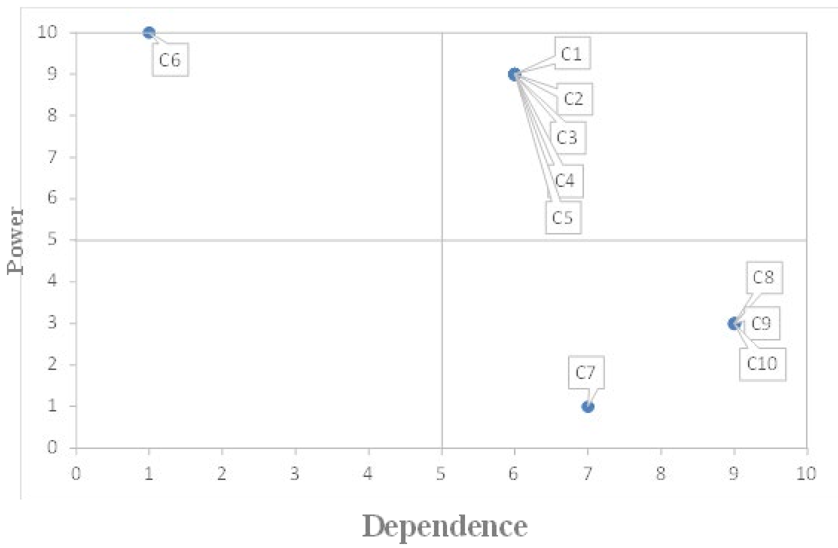

Fig. 7. Analysis of MICMAC

other fields. Generally, the studies conducted in this area have been in the form of review articles, and few of them have addressed the multi-criteria decision-making methods in supply chain 4.0. According to the supply chain 4.0 literature, the lack of identification of supply chain 4.0 technologies has made industries unable to understand supply chain 4.0. Govindan et al. (2022), in review research, investigated the enabling technologies of Industry 4.0 in supply chain 4.0, which include the IoT, cyber-physical systems, augmented reality, cloud computing, big data, and artificial intelligence. Zekhnini et al. (2022) identified the risk factors of supply chain 4.0 in their study and analysed them using the ISM method. Terra et al. (2021) investigated the barriers to world-class production in Industry 4.0. According to their

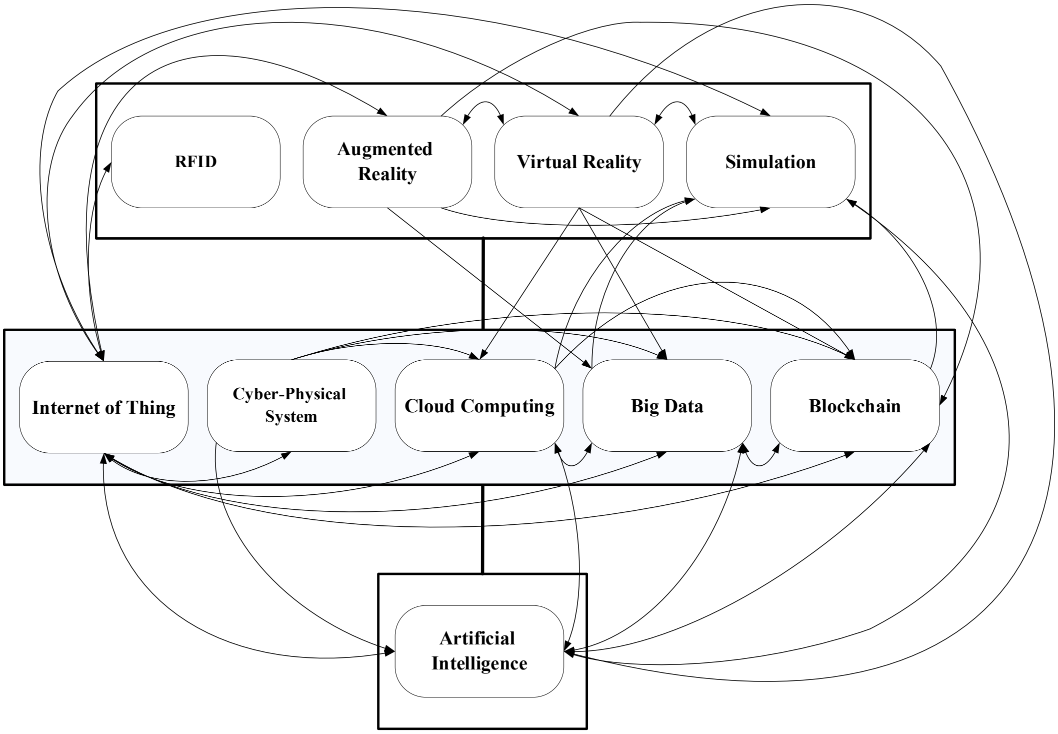

Fig. 8. Relationships within the levels of supply chain 4.0 technologies

findings, the lack of internal processing knowledge, lack of using the correct technologies, and trained manpower are the biggest obstacles in this regard. The sustainable use of resources, including manpower, enables the use of technologies in improvement projects through the reorganisation of work methods and the use of the correct techniques and tools. In practical terms, the direct efforts towards continuous monitoring of processes and use of data for project improvement, mutual training of human resources, and technology applications have been determined according to the strategic plan of Industry 4.0 trends. Szum (2021) studied digital tracking development through IoT sensors and image processing technologies. Łabędzka (2021) stated in his study that small and medium-sized enterprises (SMEs) speed up the dissemination of Industry 4.0 technologies, which consequently leads to innovation in the supply chain area. Intalar et al. (2021) indicated in their study that QR codes, IoT tools, and video cameras are used in performing image processing and tracking production status. Ali and Aboelmaged (2021) conducted a study in which they identified the drivers and obstacles of supply chain 4.0 in the food industry. According to their findings, the drivers of the supply chain include rapid changes in consumer needs, cost optimisation, threats of legal penalties, and reduction in supply-demand misalignment. Cañas, Mula and Campuzano-Bolarín (2020) investigated the supply chain 4.0 sustainability by reviewing the literature. In their study, considering the three main dimensions of sustainability, namely, economic, social, and environmental aspects, the researchers of this study identified and classified the articles in this field and found that in the literature on supply chain 4.0 sustainability, more attention has been paid to the environmental dimension and less attention has been paid to the social dimension. Sobb et al. (2020) studied the nature of supply chain 4.0 in the military industry. They acknowledged that the general infrastructure of supply chain 4.0 consists of blockchain, artificial intelligence, cyber-physical systems, and IoT technologies. Ramirez-Peña et al. (2020) categorised the critical technologies of Industry 4.0 in the supply chain 4.0 sustainability of the shipbuilding industry by reviewing the literature. According to their findings, some enabling technologies in supply chain 4.0 include big data analysis, cloud computing, augmented reality, artificial intelligence, blockchain, IoT, and simulation. They also investigated the sustainability of supply chain 4.0 in the aerospace, navy, and automotive industries. According to their findings, all three sectors have a strong interest in absorbing the IoT in supply chain 4.0. Moreover, they found that blockchain and big data technologies contribute to supply chain 4.0 sustainability more than other technologies in all three sectors.

Princes (2020) declared that digital tools such as big data analysis, artificial intelligence, IoT, and blockchain are suitable for facing the destructive challenges in supply chain 4.0. Frederico et al. (2019) proposed a framework for supply chain 4.0 in their study. This framework comprises four parts, including process and performance requirements, strategic outcomes, managerial and capabilities supporters, processes performance requirements, and technology levers. Some of the technologies used in the technology levels of this framework include IoT, cyber-physical systems, blockchain, automation, cloud technologies, augmented reality, RFID, and robots.

Scavarda et al. (2019) studied the supply chain 4.0 sustainability in the healthcare sector. According to the results of their study, social responsibility plays an essential role in the healthcare supply chain 4.0 sustainability through the IoT. Makris et al. (2019) acknowledged that big data, cloud computing, and 3D printer technologies are critical technologies in supply chain 4.0. Perussi, Gressler and Seleme (2019) investigated the equipment used in supply chain 4.0. According to their findings, for the operations inside industries and warehouses, the best equipment is the self-guided vehicle, and for delivering the product to the customer, the best equipment identified is the drone.

According to the results of the literature review, the enabling technologies in supply chain 4.0 are the same as the technologies identified in the present study. Moreover, some studies referred to the high importance of IoT in supply chain 4.0, which is in line with the finding of this study, in that using the DEMATEL technique in the current study, IoT is found to be of great importance. Of course, the results of this study can be a prelude to further research in the industries. Considering the study's limitations, we can refer to the lack of full implementation of supply chain 4.0 and the lack of experts familiar with supply chain 4.0 in industries.

Conclusions

With the transformation in manufacturing due to the Fourth Industrial Revolution, customer expectations have increased, and products have moved towards customisation and specialisation. Therefore, to maintain a competitive advantage, stakeholders must be willing to accept the Fourth Industrial Revolution and invest in it. On the other hand, it is undeniable that the supply chain is an essential part of the production, and it needs to be given priority in development and investments. Therefore, it is necessary to focus on supply chain 4.0 and adapt it to today's world and optimise it. Supply chain 4.0, with its core technologies, reduces costs and improves efficiency and effectiveness and requires organisations to identify new customer needs and solve problems related to meeting these needs and customer expectations in improving productivity. Supply chain 4.0 is characterised by high flexibility, greater agility, careful examination of details, and high efficiency.

According to the results of the conducted studies in this area, it was found that the lack of identification of the supply chain 4.0 technologies has caused the lack of understanding of supply chain 4.0 by industries. Therefore, to fill this gap, this study first identified these technologies and then investigated the relationships among them. This study aimed to investigate the relationships among supply chain 4.0 technologies using DEMATEL and ISM methods so that, by learning and understanding these relationships, the industries could implement supply chain 4.0 technologies in their supply chains and solve their related problems. To achieve this, supply chain 4.0 technologies were first identified in the research literature. Then, they were extracted using the Delphi method and experts were interviewed. Finally, supply chain 4.0 technologies were examined using the DEMATEL and interpretative structural modelling techniques. The DEMATEL technique identified the relationships between cause-and-effect technologies and found that IoT technology was more critical compared to others. The interpretative structural modelling technique found that radio-frequency identification (RFID), virtual reality, augmented reality, and simulation technologies should be deployed in the organisation first, while IoT technologies, cyber-physical systems (CPS), cloud computing, big data, blockchain, and AI should be deployed later. The MICMAC analysis found that artificial intelligence technology is independent. According to the DEMATEL technique results, this technology has a relationship with simulation technology, which is in the first level of the interpretative structural modelling technique, and IoT technologies, cloud computing, big data, and blockchain that are in the second level of the interpretative structural modelling technique.

According to the previous studies, little research has been done in the field of supply chain 4.0 technologies to be categorised and reviewed. The present study is a pioneer in this regard. According to the findings of the present study, researchers and industrial managers are recommended to pay special attention to the Industry 4.0 technologies examined in this study as the drivers of supply chain 4.0. These drivers can be implemented in future research in the industry, and their results can be discussed. These technologies can also be investigated and studied using other decision-making techniques. It seems that future research will go towards prioritising obstacles to the supply chain 4.0 implementation because to accept supply chain 4.0, it is essential to identify its barriers. Investigations of the relationships between supply chain 4.0, digital products, and Industry 4.0 can also be the possible subjects of future studies. Information security solutions in supply chain 4.0 can also be studied in the future. Supply chain 4.0 allows organisations to move from the traditional static and slow situation to dynamic, fast, and flexible frameworks. In this way, organisations can operate with simple and abundant access and without time or place restrictions. Furthermore, they cannot move without considering business processes and computer systems.

Traditional business approaches create substantial costs due to the inability to provide complex and diverse products, but new approaches seek to provide the needed services and products to the changing global markets. This issue is possible based on the combination of traditional business networks and communications and work interactions with the help of information and communication technologies.

There is a limited number of studies in the literature on supply chain 4.0, and many research gaps have remained unanswered. Due to the industries' lack of knowledge about the concepts and applications of supply chain 4.0, there are few operational experiences in this regard, and having access to experts who have complete mastery of the subject is also one of the limitations of this study.

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Supplier selection and procurement in SMEs: insights from the literature on key criteria and purchasing strategies

Ana Cristina Ferreira Ângela Silva

ABSTRACT
Effective strategic purchasing and supplier selection in companies provides businesses with leverage in acquiring goods and services. Thus, companies are in a better position to negotiate prices, discounts, delivery times and logistic channels. Also, strategic purchasing allows for performing a risk assessment to ensure the company's profitability. This research aimed to identify the key currently deliberated by SMEs for supplier selection, considering such purchasing strategies as (1) cost reduction, (2) risk management, (3) global sourcing, (4) total quality management, (5) sustainable management and (6) supplier management. Also, it aimed to identify the emerging issues related to purchasing strategies. This research work performed a content analysis following a literature review. The Scopus indexation database was selected to conduct the document search. After the refinement process, based on 59 analysed documents, bibliometric assessment tools were applied to identify the key criteria for supplier selection. The TOP6 highest ranked criteria, which corresponds to 80 % of the most referred criteria, include: (1) the quality of goods; (2) compliance with the delivery times; (3) price/cost; (4) supplier reputation and/or market positioning; (5) geographical location; and (6) supplier performance history. The goal of strategic purchasing is to support the companies in achieving long-term goals through its integration into the company's strategic planning process. It should be identified by the managers as an important resource. Several factors elevate the importance of strategic purchasing, namely, environmental protection, technology advances related to logistics 4.0, and risk assessment related to global sourcing and sustainability. The present research is in line with the findings of the referred literature, i.e., the application of prioritised criteria for the procurement and supplier selection operations in the industrial context, aiming to reduce lead times and logistic costs. The criteria must be aligned with the purchasing strategies adopted by the companies. The manuscript aims to demonstrate that the fundamentals of strategic purchasing strategies can contribute to the improvement of the SME supply process with the application of simple and cost-effective approaches.

KEY WORDS
supply chain management, strategic purchasing, supplier selection

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Ângela Silva

Instituto Politécnico de Viana do Castelo, Portugal
University of Minho, Portugal
ORCID 0000-0001-7448-291X

Corresponding author:
email: angela.a@esce.ipvc.pt

Ana Cristina Ferreira

University of Minho, Portugal
Universidade Lusíada, Portugal
ORCID 0000-0002-4775-5713

Introduction

Until the early 2000s, the focus of SMEs was more centred on the customer and their requirements, whereas supplier selection and purchasing were not afforded the same importance. However, with the growing competitiveness of the world market, companies are more willing to establish stronger relationships to achieve the required quality and good market prices. For a long time, companies have been choosing their suppliers solely based on the price and

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compliance with delivery times. Over time, this method was understood to be inefficient, and the need arose to include more criteria.

Nowadays, supplier selection is among the most important strategies to increase SME market competitiveness. Technological innovations are transforming the industrial sector. Procurement has become faster due to digitalisation, the Internet of Things (IoT) and process robotisation. As a result, production and operations are becoming more demanding at every stage of the supply chain: strategic procurement, supplier selection, process manufacturing and distribution to customers (Manavalan & Jayakrishna, 2019). Fast information exchange, short production deadlines and the quality level of products and services have encouraged companies to implement purchasing strategies.

Recently, the supplier selection and procurement in SMEs have drastically changed, mostly due to the need to adapt purchasing strategies to societal changes, i.e., scarce high-added-value raw materials; market mutability due to a pandemic or a war in Europe; the impact of logistic costs and transportation due to the rising fuel costs; and the increased concern with the industry's impact on climate change. This study aims to consider the paradigm changes in the supplier selection process. Thus, it is crucial to understand the best strategies companies implement to enhance the nexus between procurement, supplier selection and strategic purchasing.

This study aims to identify the key criteria currently used by SMEs for supplier selection, considering the most relevant purchasing strategies identified in the literature: (1) cost reduction; (2) risk management; (3) global sourcing; (4) total quality management; (5) sustainable management; and (6) supplier management. Also, it aims to identify emerging issues regarding purchasing strategies. From the methodological point of view, based on the proposed research question, a content analysis of the literature was performed. The Scopus database was selected to conduct the documental search. After the refinement process, and based on 59 documents, bibliometric assessment tools were applied to support the literature analysis.

The first section presents brief notes regarding the literature review. After a contextualisation, the analysis was divided into three parts: the most important aspects of strategic purchasing strategies, the most relevant criteria for supplier selection in the literature, and the emerging issues regarding the purchasing strategies. The second section explains the methodological approach used in this study. The listed research questions are followed by the protocol for the literature review. The third section presents the most relevant insights drawn from the study. This section presents correlational bibliometric maps and the remarks from content analyses. Based on this latter assessment, the supplier selection criteria are then presented and ranked. The fourth and last section presents the main research conclusions.

1. Literature review

Strategic purchasing and supplier selection are two aspects that directly affect the procurement function, which affects Supply Chain Management (SCM) (Huemer, 2006). Supplier selection and purchasing strategies are key aspects of SCM decision-making. Both processes are critical for increasing the company's competitiveness (Carr & Pearson, 2002; Carr & Smeltzer, 1997). A suitable supplier selection can decrease product lead time, reduce purchasing costs, improve profits and contribute to customer satisfaction. To do so, companies require the assessment of different alternative suppliers based on different criteria. Managers need to know how to give the best answers to the growing demands of customers in terms of delivery times, product availability, cost of stock ownership and reliability of operations (Belekoukias et al., 2014). From a strategic perspective, it is necessary to make a joint assessment of the processes and make decisions that maximise the benefits as a whole, where the purchasing strategies and the supplier selection criteria have a preponderant role (Fernie, 2014; Saengchai & Jermsittiparsert, 2019).

1.1. Strategic purchasing strategies

Large organisations are continually investing in the development of their purchasing departments to face the competitiveness of the market, which is increasingly globalised. In the past, purchasing was seen as a support department, and many companies did not even have it. Each department made its purchases according to its needs, without any procedure or process. Cases were possible when different departments worked with the same supplier but had different prices for the same product/service, creating discrepancies and wasting resources. Nowadays, the purchasing department is considered a strategic area that needs attention from all organisations operating in different fields and dimensions to be competitive.

Strategic purchasing is defined as the process of planning, implementation, evaluation, and strategic control and operational purchasing decisions to define all the activities of the purchasing function consistently and aligned with the company's long-term objectives (Carr & Smeltzer, 1997). The goal of strategic purchasing is to support the companies in achieving long-term goals through its integration into the company's strategic planning process; it should be identified by the managers as an important resource (Carr & Pearson, 2002).

The impact of purchasing, supplier involvement in strategic purchasing and its impact on firms' performance have been analysed in the literature (Carr & Pearson, 2002; Ondoro et al., 2013; Schütz et al., 2020). Some authors believe that purchasing and supplier involvement has a positive impact on strategic purchasing and strategic purchasing has a positive impact on performance (Carr & Pearson, 2002).

A case study of public bus transport firms in Kenya analysed the role of strategic purchasing and supply management practices in firms' performance and statistical treatment of data obtained by a survey of 183 senior executives of public bus transport firms. The survey results indicated that public bus transport firms practising strategic purchasing and supply management had improved their performance (Ondoro et al., 2013).

More recently, Schütz et al. (2020) derived a theoretical framework for examining how purchasing knowledge and integration impact cost and strategic performance, demonstrating that purchasing knowledge is a major antecedent for savings and strategic purchasing performance, emphasising the role of purchasing integration.

Nowadays, other factors are elevating the importance of strategic purchasing, namely, environmental protection (Bohari et al., 2020; Garzon et al., 2019), technology advances related to logistics 4.0 (Hasan et al., 2020), the risk assessment related to global sourcing (Hawkins et al., 2020; Wong, 2020) as well as sustainability (Rashidi et al., 2020), which implies more responsibilities for the purchasing managers. With the increasing awareness of environmental protection, supplier selection becomes an important issue for almost every manufacturer and will determine the characteristics of the final product; therefore, a performance evaluation system for suppliers is necessary to determine the suitability of the final product (Garzon et al., 2019). This issue is directly related to sustainability, which is considered imperative for societies.

In the strategic purchasing process, especially from a global point of view, one of the most important phases is supplier selection, which involves their identification, evaluation and contracting (Taherdoost & Brard, 2019). The next section presents the supplier selection activity explored in the recent literature to identify the key performance indicators used by different companies to select their suppliers.

1.2. Supplier selection criteria

The practice used by a company to identify, evaluate and establish a commercial relationship corresponds to the supplier selection process (Taherdoost & Brard, 2019). The process plays a central role in the success of any organisation because it is responsible for moving a considerable amount of capital. Since capital is a finite resource, a correct supplier selection reduces purchasing risk (Adeinat & Ventura, 2018; Taherdoost & Brard, 2019; Wong, 2020).

Based on the literature review, the most cited criteria were technology and capability, cost, delivery, price and production capacity. Relative to the supplier selection methods, they identified different method classes, namely, statistical, multi-attribute decision-making, cost-based, mathematical programming, artificial intelligence and combined (Brewer et al., 2019; Germain et al., 2011). The overall research on the supplier selection criteria and the supplier evaluation methods allows to optimise the process of supplier evaluation and selection as a sequential process of several steps (Taherdoost & Brard, 2019):

- Recognising the need for supplier selection;
- Identifying the key sourcing requirements;
- Determining the sourcing strategy;
- Identifying the potential supply sources;
- Reducing the suppliers' number in the selection pool;
- Determining the method of supplier evaluation and selection.

Numerous studies identified several criteria applied to supplier selection. The most important aspects include (Belekoukias et al., 2014; Pitchaiah et al., 2020; Taherdoost & Brard, 2019):

Long-term relationships purchasing;

- Delivery control system;
- Supplier's involvement in design;
- Quality of products and/or services;
- Frequent and reliable deliveries;
- Cost-based negotiation;
- Improved communications;
- Standardised containers;

- Reduced paperwork;
- Supplier's location.

Flexibility in negotiation is an important criterion mostly because it provides a total perspective of the costs and deadlines. A more effective commitment can be promoted by evaluating whether the supplier in question offers competitive prices and payment conditions or benefits and discounts. Price is always an important criterion since it directly affects the costs, planning of new projects and products and, consequently, the final price (Konys, 2019). The evaluation of the product or service quality is an essential criterion that directly influences the final product and customer satisfaction. Reputation is linked to historical analysis, which shows how the market sees the company in question. An important guarantee is to verify the credibility of a supplier to prevent unforeseen events and delays. Establishing efficient communication channels contributes to a strengthened relationship with the supplier. Communication that integrates end-to-end operation with technology improves understanding and interaction between all involved parties (Rashidi et al., 2020; Pitchaiah et al., 2020; Taherdoost & Brard, 2019; Zekhnini et al., 2020). Supplier's location and documentation procedures (e.g., ordering, receiving, distribution and delivering) are also relevant criteria. There is no point in producing products that fail to be delivered for a fair price and at adequate deadlines (Silva & Ferreira, 2021).

1.3. Emerging issues in purchasing strategies

Several other aspects have been emerging in recent studies as important considerations in supplier selection, such as sustainability (Ghadimi et al., 2019; Kannan et al., 2020; Rashidi et al., 2020), environmental protection (green suppliers) (Gao et al., 2020; Garzon et al., 2019; Oroojeni Mohammad Javad et al., 2020), and resilience, risks and uncertainty of the market (Hasan et al., 2020; Hosseini et al., 2019), (Chen et al., 2020a; Ivanov et al., 2018). Recently, a meta-literature review was conducted in the field of sustainable supplier selection, presenting exceptionally interesting remarks (Rashidi et al., 2020):

- There is a gap between the industry and academia that needs to be bridged;
- More studies in the area of global sourcing are required;
- Outcomes of different supplier evaluation methods should be compared;
- There has been no major shift or change in the traditional supplier selection practices;
- The ratio of the applied social criteria is relatively low compared to the total number of criteria;
- The innovation capability of suppliers must be further considered;
- More studies on sustainable supplier selection are needed in the e-procurement area and such service-based industries as healthcare;
- Evaluating the sustainability of suppliers in a dynamic environment needs to be further studied.

Thus, it is important to study the complexity of the supply market, constrained by supply scarcity, quantity and quality of goods/services, logistic costs and business conditions. Also, attention should be paid in terms of the value-added by SCM in total costs and the impact on companies' profitability. All these aspects may contribute to minimising the supply chain vulnerabilities of SMEs (Gupta & Barua, 2017; Pal et al., 2013; Pressey et al., 2009; Stekelorum et al., 2020).

Recently, data collection and information exchange in the industry has been increasingly assisted by digital technologies, integrated into the context of Industry 4.0, which includes multi-faceted technological approaches to improve SCM based on real-time information: industrial IoT, big data, additive manufacturing, artificial intelligence, blockchain, cloud and simulation (Matthess et al., 2022; Bai et al., 2020). Supplier selection, considering the Industry 4.0 requirements, is essential in promoting collaborative strategies between suppliers and manufacturers (Resende et al., 2021).

2. Research methodological approach

To understand the key factors to be considered in strategic purchasing in SMEs, one research and two sub-research questions were defined, as presented in Table 1. The analysis was conducted through the implementation of a literature review and the respective content analysis. Content analysis is a widely used qualitative research technique to correlate concepts within some given qualitative data.

According to Snyder (2019), this methodological approach aims to identify evidence from published research work, considering pre-specified criteria to answer a particular research hypothesis. Thus, a search is systematically conducted, depending on

Tab. 1. Definitions of research and sub-research questions

Research Question (RQ)	Sub-research Questions (sRQ)
RQ: Which key criteria that companies apply when selecting their suppliers?	**sRQ1**: What are the best purchasing strategies currently implemented by SMEs?
	sRQ2: What are the emerging issues concerning strategic purchasing in SMEs?

I
- Research question formulation: RQ and sRQ1 and sRQ2
- Planning the LR search

II
- Search database: **Scopus**
- Search by (inclusion criteria): TITLE-ABS-KEY
- No-filter on document type or scientific field — **Result with 1663 documents**

III
- R1 — **Result with 165 documents**
  Inclusion criteria: documents from the scientific field of Engineering, Management, Economics and Econometrics and Decision Sciences
- R2 — **Result with 86 documents**
  Inclusion criteria: documents published between 1990 and 2021
  Exclusion criteria: documents in languages other than English
- R3 — **Result with 59 documents**
  Only papers from peer-reviewed journals were selected for the content analysis because of their availability online

IV
- Content analysis and use of VOSviewer®. This software allows constructing and visualising bibliometric networks based on the bibliographic coupling of co-occurrence networks of important keywords extracted from the scientific literature.

V
- The best purchasing strategies and the key criteria that companies use when selecting their suppliers were identified through the content analysis
- Key findings were aggregated and summarised

Fig. 1. Methodology applied in the present research work

the availability of current research in scientific databases. The implemented methodology was based on the following five steps:

I. Unequivocally and clearly formulate the research questions and plan the review queries, addressing the main topic;

II. Select the database to be used for searching studies, defining the inclusion and exclusion criteria for the search process;

III. Based on the number of collected works, define search refinement criteria. These refinements can be related to the typology of the document (journal papers, conference papers, books, book chapters, editorial reviews, and others), the publication period interval, the scientific field (engineering, mathematics, computer science, business and management, decision sciences, among others) and writing language. A more refined in-depth search improves the analysis development;

IV. Perform a content analysis of the selected documents in the scope of the research questions.

V. Report the key findings, identifying the highest contribution of the published research on shedding light for further research (Denyer & Tranfield, 2009).

After defining the research question, the Scopus database was selected for document search. This database contains titles from more than 5 000 international publishers, including peer-reviewed journals, in the field of Logistics and Supply Chain and Operations Management. As inclusion criteria, it was considered the search by "Title", "Abstract" and "Keywords" (TITLE-ABS-KEY). Initially, the main keyword combination was: ["purchasing"] AND ["procurement"] AND ["SME"] AND ["supplier"] AND ["industry"], limiting the timeline to the period between 1990 and 2021. The steps followed while conducting this research are presented in Fig. 1.

Regarding the document typology and scientific field, no filter was considered in the first search, i.e., "all fields" was selected. As expected, many documents were obtained (over 1663). Several document types were considered: most were papers in international journals (53.5 %), followed by conference papers (37.8 %), reviews (3.5 %), book chapters (2.4 %) and short surveys (1.1 %). With these results, a three-iteration refinement was performed. In the first iteration (R1), only documents within the industrial engineering context were selected. This restriction significantly reduced the number of documents for the research (165 documents). In the second refinement (R2), all the documents that do not meet one of the following specifications were excluded: (1) not addressing the main topic issue and (2) written in languages other than English. At this point, 86 documents were available for content analysis. The number of obtained documents was reduced dramatically during this refinement iteration by eliminating documents based on the industrial context. Although with minor adjustments, the distribution of various document types remained unchanged: most were papers in international journals (68.6 %), followed by conference papers (26.7 %), reviews and book chapters with 2.3 % each. In the last refinement iteration (R3), only papers from peer-reviewed journals were selected for the content analysis (59 documents). This consideration was taken since the remaining documents are not available online. Documents that were written in languages other than English were also eliminated.

Based on the selected set of documents, a critical analysis was made. For viewing bibliometric maps, helping the analysis and discussion, the free software VOSviewer was used (van Eck & Waltman, 2020) for the construction of the co-occurrence networks maps based on indexed keywords (Szpilko & Ejdys, 2022).

3. Research results and key findings

Strategic purchasing management implies a process of negotiation, implementation, and evaluation to carry out operations and make products and services available in companies. Thus, the selection and evaluation of suppliers require the inclusion of methods and criteria adjusted to the purchasing strategy that each company adopts.

3.1. Bibliometric content analysis

The collected data was used to perform a content analysis with VOSviewer to visualise the bibliometric networks, which allowed a clear study of the topics under research. As can be seen from the bibliometrics shown in Fig. 2, the publications are distributed in four main clusters: (1) supplier selection methods, (2)

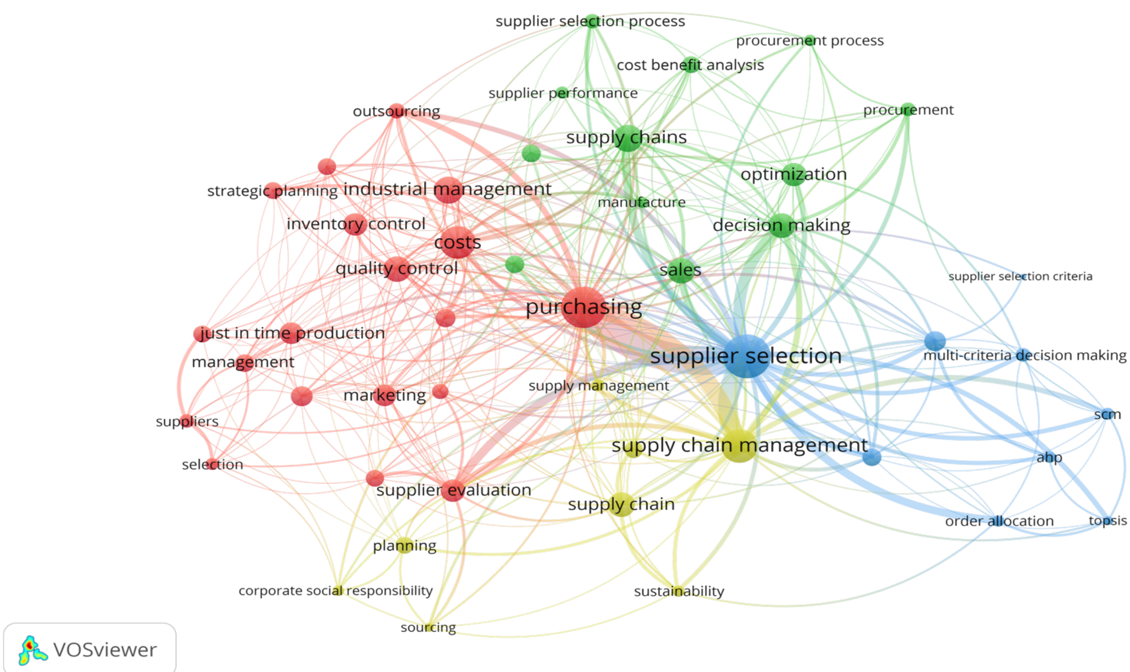

Fig.2. Bibliometric co-occurrence map of keywords for supplier selection and strategic purchases

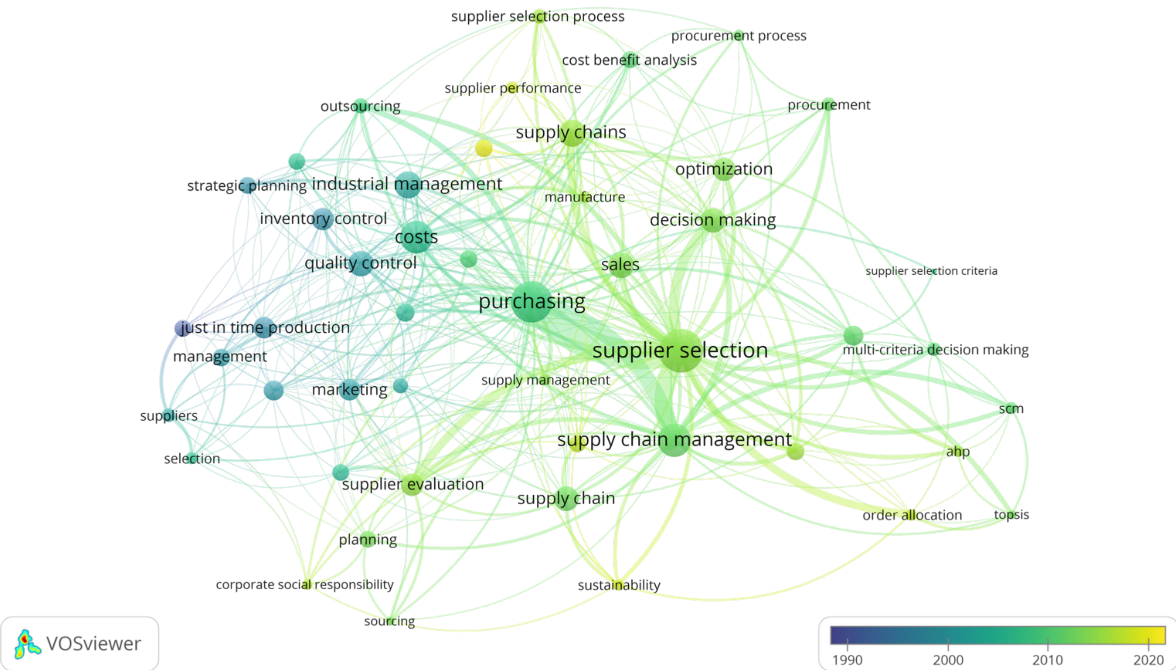

Fig. 3. Bibliometric co-occurrence map of keywords between 1990 and 2021

procurement process, (3) SCM parameters, and (4) different approaches to the decision-making process.

Regarding the parameters of supply chain management, the main issues are related to planning, the type of sourcing and sustainability considerations. The global shortage of various raw materials has affected many supply chains and resulted in growing costs. Additionally, there has been a general increase in energy and fuel prices, which, combined with the lack of materials, has generated delays in the delivery of orders and difficulties in logistics and distribution. Decision-making has mainly been based on data involvement analysis, multi-criteria decision methods, optimisation algorithms (i.e., Analytic Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Fuzzy Logic and cost-effective models.

The supplier selection criteria are analysed by considering data between 1990 and 2021. This period corresponds to the publication years of the selected papers included in the content analysis. The analysis of the map presented in Fig. 3 showed that the sustainability of supply chains is increasingly important, as well as the responsiveness of suppliers to meet the needs of production systems, mostly the ones that operate on a just-in-time basis. The current ease of communication and the use of technological tools, which allow the application of decision models in real-time, have transformed the strategic management of purchases and gained relevance in the selection of suppliers.

3.2. Identification of most relevant criteria for supplier selection

Recent changes in purchasing and supply management due to the market and logistics instability and the growing market competition have shifted the way companies perceive procurement, drawing attention to supplier-related dimensions (Garg, 2021). Such aspects as technological competences, long-term integration potential, competitiveness and the performance of a buyer are a function of the performance of service quality, delivery conditions and flexibility. Nowadays, they are extremely valuable since services, goods, and acquired raw materials can represent between 30 and 90 % of product costs (Hasan et al., 2020; Schütz et al., 2020).

The unique consideration of price, quality and delivery time is no longer a sine qua non condition in the selection of suppliers (Chai & Ngai, 2020; Ristono et al., 2018). Flexibility, reliability, location, ability to respond to special requests and the longevity of supply relationships are all referred to by studies as important factors in the selection and evaluation of new suppliers. In the manufacturing industry, such criteria as operations control, quality of packaging and shipping, warranty and claim policies are also identified as less important (Chen et al., 2020a; Hosseini et al., 2019; Jain & Singh, 2020a; Kamalakannan et al., 2020; Konys, 2019; Oroojeni Mohammad Javad et al., 2020; Rashidi et al., 2020; Pitchaiah et al., 2020; Taherdoost & Brard, 2019; Zekhnini et al., 2020).

With the recent increase in the cost of materials and the uncertainty of logistics and supply chain, supplier reliability seems to have become fundamental. This criterion is related to supplier trustworthiness and dependability. Frequently, this aspect is based on the perception of the supplier's financial stability (annual turnover and capital availability) and past and current business partnerships (Florez-Lopez, 2007).

To evaluate the relevance of each supplier selection criterion, a ranking was established, considering their relevance in the contents analysis of the selected papers, as presented in Fig. 4. The ranking was defined considering the frequency of indexed keywords and through the application of the Pareto principle. This means that the highest ranked criteria correspond to 80 % of the most referred in the literature.

Of the total of 59 analysed papers, 14 considered the "quality" criterion as the most important. In practice, different criteria are associated with the overall quality criterion, including rejection and return rates, the ratio of products rejected after inspection, the number of invoices received without errors, the quality of shipment and many others. In the papers, 12 included the criterion of "compliance with delivery time" in their lists of the most important criteria. For its quantification, criteria include, e.g., delivery delays, fulfilment of delivery requirements, lead time, and total time between order and final delivery. Price/cost is pointed out as the most important criterion in nine publications. It is reasonable to expect that purchasing managers tend to choose an alternative with a lower acquisition cost as long as technical requirements and mandatory requisites are fulfilled, determining all the costs associated with the acquisition and underlying charges (Hasan et al., 2020).

The TOP6 highest ranked criteria, which corresponds to 80 % of the most referred criteria, include: (1) quality of goods, (2) compliance with the delivery times, (3) price/cost, (4) supplier reputation and/or market positioning, (5) geographical location, and (6) supplier performance history. Together, these six criteria represent about 80 % of the most used and valued aspects across different purchasing strategies applied by SMEs in the industrial sector (Azambuja et al., 2014; Carr & Pearson, 2002; Çebi & Bayraktar, 2003; Chan & Chan, 2004; Monczka et al., 2009; Naoum & Egbu, 2016; Pal et al., 2013; Pressey et al., 2009; von Haartman & Bengtsson, 2015). It is important to mention that according to the analysis, supplier financial health and internationalisation level are the criteria with a lower priority. Indeed, supplier selection is a multiple-criteria decision-making process divided into two main steps: the determination

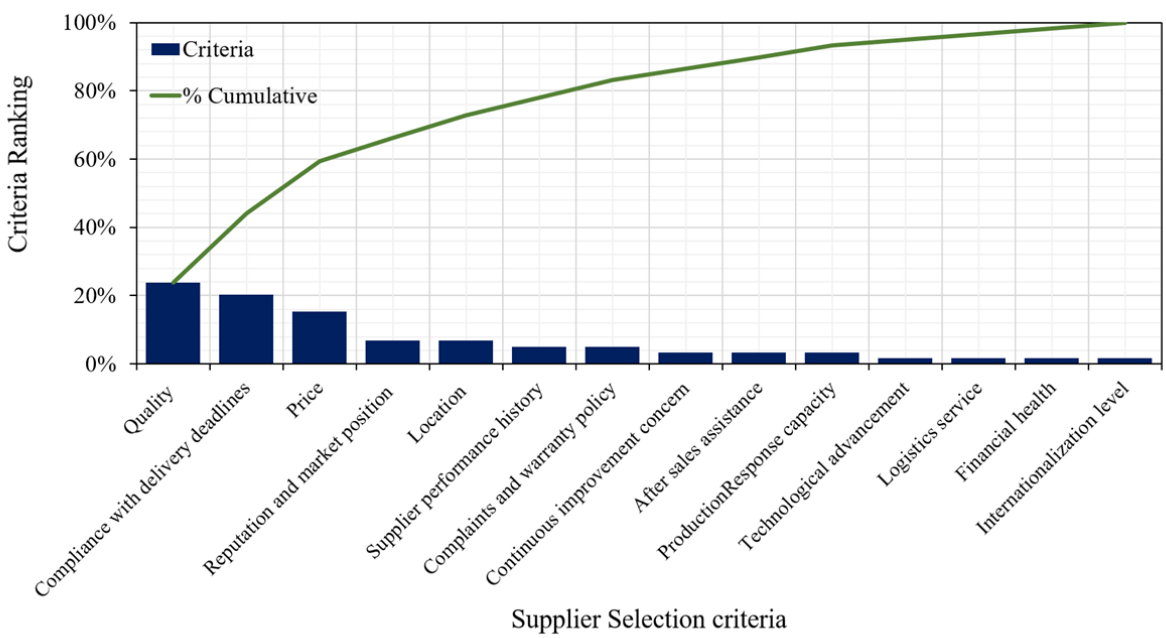

Fig. 4. Identification and classification of most valued supplier selection criteria

of weighted criteria and supplier ranking (Zimmer et al., 2016).

3.3. Purchasing strategies typically implemented in SMEs

Effective implementation of purchasing strategies contributes to clever purchasing decisions and, consequently, to their profit. From a wide point of view, the degree to which purchasing is seen as a "strategic" approach by SMEs and the implementation of an evaluation of a supplier selection process has not been addressed properly.

SMEs aim to purchase goods and/or services, respecting their requirements and specifications, at the lowest price with better delivery timings. Yet, the question arises, "Should strong supplier relationships, total quality management and sustainable practices be included in the balance without compromising the financial and business stability of companies?". There is no single recipe in terms of the best purchasing strategy to adopt. Each company in the most diverse sectors of activity and the most different markets must study the most relevant aspects of its supply chain to define its strategy (Ellegaard & Andersen, 2015; Naoum & Egbu, 2016). After a careful analysis of the literature review, six main strategies applied by SMEs were identified, as presented in Table 2.

Once purchasing strategies are identified, the next step is to establish the relationship between the supply process requirements and these strategies from an SME point of view. The requirements included in the study were defined.

In Fig. 5, a matrix of relationships is presented and an attempt to measure the intensity of this relationship is described as strong (●), moderate (○)

Tab. 2. Predominant purchasing strategies implemented by SMEs

Strategies	Supporting references	Description
Cost reduction	Mohammad et al. (2020) Azambuja et al. (2014) Carr & Pearso (2002)	In this strategy, the companies consider supplier segmentation to ensure that different categories of materials/products have appropriate cost levels. The purchasing strategy is based on comprehensive negotiation processes aiming for cost reduction along the supply chain
Risk management	Wong (2020)	Companies, especially in some segments of the industrial sector, operate on markets of some uncertainty, such as variation in demand, variation in supply, and visibility to the customer, which means that purchases need to include strategic risk analysis. Risk management strategies account for internal and external variables while establishing procurement activities
Global sourcing	Schütz et al. (2020) Konys (2019)	Global sourcing allows a company to search for suppliers with a reasonable price or fit for the specifications unavailable in the domestic market. This strategy is also applied by companies that are constantly getting ahead in innovation standards
Total quality management	Sánchez-Rodríguez et al. (2004)	It is a strategy that allows companies to increase the quality of their products while keeping the cost of supplies in a queue. There is considerable evidence indicating a strong relationship between quality and profitability, mostly if it entails such aspects as supplier certification, investment in training and support of suppliers, supplier involvement in product design, and information sharing
Sustainable management	Tunca & Zenios (2006)	It is a strategy that integrates social and environmental responsibilities into purchasing decisions while meeting the company's requirements. Thus, it can be defined as a strategy for combining the best output for the economic, corporate interests, environment and society together with quality and price
Supplier management	Seuring & Müller (2008)	This strategy includes the selection of a solid mix of suppliers who can provide the goods required to meet the company's business requests. It is usually used when suppliers cannot meet the pricing, quality and delivery times, resulting in constant market consultation and product quotation requests

or weak (▽). For each purchaing strategy, the direction of improvement was also indicated, i.e., maximise (↗), target (◇) and minimise (↘).

The supplier process requirements were chosen to consider the frequency of their citation in the literature review. The price and supplier positioning in the market are the requirements that seem to be more representative of the majority of purchasing strategies.

On the other hand, the supplier management strategy is the approach that has the strongest relationship with most of the requirements.

This outcome is partially corroborated by Qian (2014), who proposes a strategy for supplier selection based on the combination of decision factors: price, service level, delivery time and supplier reputation.

The quality of provided products/services has a strong relationship with costs reduction and total quality management strategies since quality implies investments, namely, in quality certifications, to provide warranties to customers, which sometimes is a requirement of the client (Konys, 2019; Tunca & Zenios, 2006).

Compliance with delivery deadlines is a crucial requirement for all companies, especially in the actual global and unstable market, which has an enormous impact on supply chain performance, since companies, even SMEs, try to implement the Just-In-Time and Lean philosophy, which implies a direct dependency of the delivery deadline compliance of their suppliers.

3.4. Emerging aspects of purchasing strategies

Supplier selection and procurement in SMEs have changed due to the need to adapt purchasing strategies to the most recent challenges: scarce mate-

Supplier selection criteria	Purchasing strategies					
	↘	↘	◇	↗	↗	◇
	Cost	Risk management	Global sourcing	Total quality management	Sustainable management	Supplier management
(1) Quality of products/services	●	▽	○	●	○	○
(2) Compliance with delivery deadlines	○	○	●	▽	▽	○
(6) Supplier performance history	▽	○	○	●	○	●
(8) Complaints and warranty policy	○	○	○	●	●	●
(10) Supply response capacity	●	○	●	○	▽	●
(3) Price/cost	●	○	●	●	○	●
(5) Location	●	●	●	▽	○	○
(7) Continuous improvement concern	●	○	▽	●	○	●
(4) Supplier reputation and market position	▽	●	○	●	●	●
(11) Technological advancement	●	●	○	○	○	●
Strength of supply process requirements in Purchasing Strategies	76%	68%	72%	76%	60%	88%

Fig. 5. Supply process requirements versus purchasing strategies

rials and their availability on due times, economic market mutability, the impact of logistic costs and transportation due to rising fuel costs, and climate change. Thus, some emerging issues regarding purchasing strategies are reported in the most recent papers. Smart, sustainable, social and environmentally responsible supply chains are some of the most cutting-edge dimensions of purchasing strategies (Brady et al., 2018; Chen et al., 2020b; Eggert & Hartmann, 2021; Florez-Lopez, 2007; Jain & Singh, 2020b; Shen et al., 2021; Stekelorum et al., 2020; Zimmer et al., 2016). Due to environmental policies and legislation demands and social accountability before their stakeholders, companies have introduced other emerging requirements into their purchasing strategies.

Table 3 summarises some of the current issues based on the reduction of supply chain logistics, the environmental impacts and the need for certification in terms of quality and environmental management systems (Sánchez-Rodríguez & Martínez-Lorente, 2004; Shen et al., 2021; Stekelorum et al., 2020; Winter & Lasch, 2016; Zimon & Zimon, 2019).

Conclusions

The paper presented research on identifying the main criteria adopted as a key aspect in a company's supplier selection. The study was performed considering the content analysis of a literature review based on a proposed research question. The Scopus database was selected to conduct the document search. After the refinement process and based on 59 documents, bibliometric assessment tools were applied to support the literature analysis. Regarding the main research question, "Which are the key criteria that companies seek when selecting their suppliers?", the TOP6 high-

Tab. 3. Predominant purchasing strategies implemented by SMEs

Requirements	Supporting references	Description
Reduction of logistic supply chains	Gao et al. (2020) Schütz et al. (2020)	Nowadays, the supply chain is engineered to be agile, flexible and customised. Advanced communication tools, IoT technologies and the digitalisation of processes in the industry have been used to enhance SCM practices and reduce the logistic steps. The technological capability of a supplier and its ability to acquire new technical knowledge greatly impact the supply chain length
Environmental impacts	Gualandris et al. (2014) Haeri & Rezaei (2019)	It is urgent for companies to contribute to minimising the climate change problem by reducing the so-called greenhouse gas (GHG) emissions associated with the transportation and delivery of goods. Decreased delivery time and transportation distances actively contribute to emissions and pollution reduction. Also, companies are nowadays more invested in choosing suppliers based on their responsibility to use natural resources carefully, minimise damage and ensure resource availability for future generations
Quality and Environmental Management System	Zimon (2019) Garzon et al. (2019)	In many sectors of activity, such as the automotive, food industry, medical devices and others, the selection of a supplier implies the need for certification of quality and environmental performance. Thus, the supplier selection can depend on implemented ISO 9001 standards (Quality Management System) and/or adopted the ISO 14001 standard (Environmental Management System), establishing a beneficial synergy between quality and environmental performance
New Technologies Integration	Matthess et al., 2022 Bai et al., 2020 Resende et al., 2021	Industry 4.0 relates to several new or enhanced core capabilities, expressed through new technology areas: more intelligence and integration in business processes, proximity to the client, closing the loop, smart products and services, business connectivity and intimate human–machine collaboration

est ranked criteria were identified. The most relevant criteria included (1) the quality of goods, (2) the compliance with delivery times, (3) price/cost, (4) supplier reputation and/or market positioning, (5) geographical location, and (6) supplier performance history. T

he content analysis has shown that the selection and evaluation of suppliers presume a process where the evaluation criteria are in the scope of the purchasing strategy and the main interests of the procurement department. The definition of these criteria is fundamental not only for supplier selection but also for their evaluation.

The choice of inappropriate criteria can result in wasted time and resources and reduced profit margins. More recently, the price criterion has no longer been seen as simple as the unit price but rather the total cost from a purchase order. The content analysis also showed that the publications were mostly distributed in four main clusters: (1) supplier selection methods, (2) the procurement process, (3) SCM parameters, and (4) different approaches to the decision-making process.

Regarding sub-research question sRQ1, "What are the best purchasing strategies currently implemented by SMEs?", the purchasing strategies identified in the literature are (1) cost reduction, (2) risk management, (3) global sourcing, (4) total quality management, (5) sustainable management, and (6) supplier management. SMEs are powerfully affected by the purchasing function efficiency. Depending on the adopted purchasing strategy, different requirements have a specific impact on the way the supplier is selected. Nevertheless, cost-based negotiation still has great relevance in the decision-making process. The study allowed to conclude that strategic purchasing is nowadays perceived as a cornerstone for organisational development and competitivity.

The study also allowed answering sub-research question sRQ2, "What are the emerging issues concerning strategic purchasing in SMEs?". The reduction of logistic supply chains, the environmental impacts and the integration of quality and environmental management systems are the emerging aspects pointed out by the literature regarding purchasing strategies.

The development and implementation of a survey of Portuguese SMEs is proposed as a future study subject. The focus is to develop a conceptual model for supplier selection and a simulator considering the weighted parameters from the decision model.

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Study on the improvement of medical service quality in Beijing's Tianqiao Community Health Service Centre

Qiong He Qixiao Li Jindong Chen

ABSTRACT
Within the context of the COVID-19 pandemic, community-level medical institutions as health service centres have been gaining importance in the medical reform expansion. As prior research has not fully addressed how to index and evaluate the quality of medical service, this article proposes a framework based on the service quality gap theory and the three-faceted "structure–process–outcome" quality evaluation theory. The study took the medical services at Beijing's Tianqiao Community Health Service Centre as an example to construct an index system for medical service quality evaluations. Data was collected from 211 people, and SPSS software was used for data processing and analysis. Due to the COVID-19 pandemic, patients without serious diseases tend to choose community hospitals to reduce their infection risk. As a result, they have growing requirements for clinics to have more departments and specialists. The studied community health service centre has encountered difficulties connected to low patient expectations, a poor medical environment, outdated hardware and equipment, and a low level of medical services. Some suggestions have been made to add specialised departments and consider the convenience of medical treatment for the elderly.

KEY WORDS
community health service centre, quality improvement, service quality, SERVQUAL model

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Qiong He

Beijing Information Science and Technology University, China
Laboratory of Big Data Decision making for Green Development, China
ORCID 0000-0002-2208-4896

Corresponding author:
e-mail: q_he100085@163.com

Qixiao Li
Beijing Information Science and Technology University, China
Laboratory of Big Data Decision making for Green Development, China
ORCID 0000-0003-4239-1321

Jindong Chen

Beijing Information Science and Technology University, China
Laboratory of Big Data Decision making for Green Development, China
ORCID 0000- 0002-7841-9608

Introduction

Community health care is a critical component of primary health care. Community health service centres play a positive role in solving prominent social problems related to the availability of complex and expensive medical treatment to the public, reducing the cost of medical treatment for most patients and promoting the harmonious development of the doctor–patient relationship. Community health service centres have become an inevitable development

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trend in China, aiming to build an urban health service system based on comprehensive community health services. By 2020, China had set up 35 365 community service centres ("stations"), of which 9 826 were community health service centres, providing services to 620 million people nationwide. In recent years, the state has continuously increased its support to the medical and health fields, and the fifth plenary session of the 18th CPC Central Committee of China has elevated "building a Healthy China" to the status of the national strategy (Dong, 2018). China's new medical reform policy priorities the upgrading of community health care. Support for community medical care has been gradually improved. Attention should be given to the medical efficiency of community health service centres.

The relationship between doctors and patients has always been a hot issue in society, and the quality of medical service directly influences people's medical care experience. At present, China's medical and health systems are in the key stage of in-depth reform. Problems, such as low utilisation rate of medical resources, high medical costs, and failure to provide guarantees of treatment efficacy, have become targets of this medical reform. Over the years, the state continuously increased policy support and capital investment in medical and healthcare fields and made the quality improvement of medical services a focus for the future work of the medical industry. As community-level medical institutions, community health service centres have wide coverage of special features and provide convenient access to medical services for the public. However, such medical institutions as community health service centres now face many problems, including inadequate medical facilities, a lack of competent medical workers, a "reversed triangle" pattern of resource structure etc., indicating an urgent need for improvement of the medical service quality.

Community health service centres, as primary medical facilities in the medical system, conveniently provide a wide range of medical treatment to the people under their jurisdiction. A community health service centre is a major source of primary health care for millions of Americans (Maggi et al., 2020). High-quality medical services can meet different health service needs of the people to improve the satisfaction level. Against the backdrop of the COVID-19 pandemic, community health service centres as community-level medical institutions have been gaining importance in medical reform. On the one hand, because of the routine COVID-19 control, community health service centres are shouldering a heavier workload to provide public health service, epidemic detection, and routine epidemic prevention within their communities. On the other hand, community-level medical institutions should help ease the burden of larger hospitals when secondary and tertiary medical institutions get overcrowded. In addition, the reform poses new challenges to community health service centres, such as intelligent medical care and more diverse patient needs. However, most existing quality evaluation standards focus on the static analysis of aftercare results and expenditure while ignoring the dynamic quality management process of provided medical services, which is unsuitable for the current quality development status of medical services. The design of a reasonable and efficient evaluation framework becomes essential for solving these problems.

Many local and foreign scholars have conducted extensive studies on improving the quality of medical services. Ehlke (2018) examined the historical forces and antecedents that helped shape community health centres. Though the current iteration of community health centres dates back to the 1960s, their predecessors existed at the beginning of the 20th century. They mostly started as an urban phenomenon and rode the wave of the wider political programme and socioeconomic reforms of the Progressive Era (Ehlke, 2018).

The research on service quality began in the late 1970s. Lewis and Booms found that service quality has become the key basis for measuring customer service of enterprises (Lewis & Booms, 1983). In recent years, researchers have focused on the design of a service quality evaluation system. Parasuraman et al. proposed a conceptual service quality model, hoping to stimulate the interest of academia and quality service practitioners in providing a framework for further empirical research in this important field (Parasuraman et al., 1985; Yerdavletova & Mukhambetov, 2015). Ayanian included patient care in the medical quality evaluation system (Ayanian & Markel, 2016). Martin et al. (2016) found that the results of doctor rating websites had a positive impact on patient care. Fayissa et al. (2020) conducted a quantitative study on the classification rules for health care service quality in the nursing home industry.

The study found that the quality evaluation of community medical service has attracted much attention. Ai (2020) established the evaluation index system of Shanghai Medical and Health Care Integrated Community Medical Service by SPO. Finnish scholars believed that the quality of medical service could be assessed by evaluating such indicators as treatment information, integrity, politeness, service professionalism, service awareness, disease development, privacy protection, test efficiency, and overall treatment success rate (Hiidenhovi et al., 2021).

Many scholars believe that heterogeneity factors will affect the quality of the evaluation. Meng et al. (2017) studied the construction of Internet Plus intelligent hospitals. Bowblis & Smith (2018) explored the impact of occupational licensing on service quality for community workers. Based on SERVQUAL evaluation, Al Borie & Sheikh Damanhouri (2013) studied the satisfaction of medical service quality at public and private hospitals in Saudi Arabia and found that service quality had a certain impact on medical care strategies. Shi (2019) studied the improvement of community medical service using a patient experience survey based on the PPE-15 questionnaire. Du (2020) analysed the defects of public hospital service quality based on the five aspects of the SERVQUAL model.

Although no unified definition of medical service quality exists, Brook pointed out that "a good quality of medical service should guarantee high technical quality and should guarantee that the patients can receive loving and culturally appropriate treatment and fully participate in the decision-making of treatment plans". This means that the quality of medical service includes not only traditional factors, such as accuracy, timeliness, and diagnostic integrity, but also new ones, such as patient satisfaction with the effectiveness of medical services, respect perceived by patients, medical service efficiency, medical continuity, a systematic approach, etc. (Robert et al., 2000). Wen Jie formulated targeted measures to improve the quality of medical services in a health centre. Such measures have promoted the health centre's overall service capacity and given it a competitive edge compared to the competition (Jie, 2018).

The necessity to optimise the evaluation system for quality medical service is undeniable. Hou Xiong pointed out the problems existing in the service quality of Internet hospitals by developing the index system for their service quality evaluation and applied the Kano model analysis method to propose targeted improvement strategies for promoting a beneficial attitude regarding the development of Internet hospitals (Xiong, 2020). Larry et al. (2002) described the establishment of an on-site pharmacy in community health centres (CHC) to improve access to medications for impoverished patients, the implementation of pharmaceutical care programmes and clinical pharmacy services to improve patient care and therapeutic outcomes, and the development of an ambulatory care site for training pharmacy students. Wei Haizhu et al. took Hainan medical service practice as an example to study the optimization of medical service quality (Wei & Dong, 2020).

By constructing a theoretical model, Hasan (2012) evaluated the quality of primary health services in rural Bangladesh from structure to process and then to results. Structural dimensions included a lack of medical staff and absenteeism, a lack of available health experts, a harsh environment, and scarce resources. Process dimensions included timeliness and accessibility of health services, consultation time, provider behaviour, referral, and emergency services. The survey results showed that the lack of medical and health experts, inappropriate use of resources, slow health providers, and service consultation dominated by service providers would lead to low service efficiency and patient dissatisfaction (Hasan, 2012).

Chinese scholars also carried out relevant studies. Quan et al. (2018) pointed out that the current development of domestic community health service institutions is lagging behind, has a weak foundation and declining relative development ability, so it is urgent to build a good strategic ecosystem. They mainly highlighted two aspects. First, at the institution's construction and management level, the health service institutions in most urban communities show imbalance, which is mostly caused by regional differences, specifically reflected in the layout and business development of institutions.

Second, the internal services and guarantees for urban communities are insufficient, i.e., there is a certain gap between the institutions' business skills and the people's new requirements for health and sports services, the number of family doctor service teams is insufficient, the composition and structure of teams are unreasonable, the allocation and updating speed of medical equipment has not reached the required level for basic diagnosis and treatment, and the construction of information platforms needs to be strengthened. The management level, the distribution mechanism, and the salary system need to be improved (Quan et al., 2018). By comparing the primary care quality in China and the United States, Liu (2016) constructed an evaluation framework for the quality of community-level medical and health services based on input, process, outcome, and quality evaluation methods.

To sum up, local and foreign scholars have already analysed the medical service quality in different types of institutions from the patient's perspective. Most authors agree that the quality of medical service determines whether patients are willing to obtain medical service at community health service centres. More people choose community health service institutions for medical treatment in China, which can promote the rational use of China's medical resources and form good practice. The following hypotheses are proposed based on the discussion above:

Hypothesis 1 (H1): The quality of medical service affects patient intentions.

Hypothesis 2 (H2): Community health service centres encounter low patient expectations and have inadequate environment, hardware, equipment, and medical level.

This study focuses on building an index system for the evaluation of the medical service quality of the primary medical facilities to provide an empirical context to describe and measure factors applicable to Chinese scenarios. Three main research questions are addressed: (1) How to build an evaluation index for the medical service quality while achieving both process quality and result quality? (2) Does the quality of medical service affect patient decisions? (3) What are the problems encountered by community health service centres? To answer these research questions, the authors present an evaluation model under the framework of Donabedian's structure–process–outcome theory and the SERVQUAL evaluation scale. The analysis of the data collected by a questionnaire survey showed that the quality of medical service is one of the principal factors affecting patient decisions. Also, the empirical results demonstrated that low patient expectations and inadequate environment, hardware, equipment and medical level might be the basic problems of community health service centres.

This study, therefore, makes three main contributions. First, it provides definitions, measurements and principles for building an index system for the evaluation of medical service quality. Second, it uses an example in China to examine the relationship between the quality of medical service and patient intentions.

The empirical results prove the rationality of the index system constructed in this study. Third, it examines several problems in community health service centres. SWOT analysis helped to identify reasons for advantages, disadvantages, opportunities and threats. Also, this research effort contributes by suggestions for the improvement of medical service quality.

2. Materials and methods

An American scholar, Donabedian, first proposed measuring the three facets (structure, process, and outcome) as quality indicators to evaluate the quality of medical service. This paper attempts to use Donabedian's classic framework for healthcare assessment as a baseline for analysis (Huang et al., 2021). At present, the evaluation index of medical service quality often focuses on the "outcome" but lacks the evaluation of "structure" and "process". This study focused on how to build an index system for the evaluation of the service quality of community hospitals and then performed empirical tests. Service quality reflects the customers' perception, which is highly subjective and perceptive. Therefore, if medical and health institutions are to improve the overall service quality, they must be grounded in patient needs and their perceptions while achieving both process quality and result quality (Huang et al., 2021).

2.1. Sample and procedure

The sample for this study was a group of patients from the Beijing's Tianqiao Community Health Service Centre, including 107 male patients (50.71 %) and 104 female patients (49.29 %). This particular Centre was selected because of: (1) The complex structure of residents serviced by the Centre offers this study an applicable sample in terms of diversity and research significance, satisfying the research needs. Beijing's Tianqiao Community Health Service Centre is responsible for 46 300 residents in the area (managed by eight neighbourhood committees) in terms of providing the "Six-in-One" community health service covering basic medical care, preventive health care, rehabilitation, etc. (2) The Centre has three service stations and has established a new internal management organisation with a Health Management Department and a Performance Evaluation Department, consistent with the research purpose of the study. Unlike other institutions, the focus on service performance gave this study an innate advantage in the quality of data collection.

The data collection proceeded as described next. First, factors and dimensions were identified. Then, a research model was built to fully capture the research hypothesis. Finally, the evaluation index system was established according to the selection principle of the evaluation index, and a questionnaire was produced. The research authors contacted the Beijing's Tianqiao Community Health Service Centre to solicit their help in distributing questionnaires to their patients.

Then, the analysis focused on the main factors that influence the evaluation of the quality of medical service. Liu and Wang (2008) pointed out social demographic characteristics, external environmental factors, and a medical service organisation system as the most important three aspects of building index systems for the evaluation of the service quality of community hospitals. The authors of this article referred to the conclusions of the meta-analysis by Liu and Wang et al. to define the variables as follows:

Medical Setting means medical environment, medical facilities, and equipment.

Medical Level means the physical recovery of patients after medical treatment.

Service Attitude means the service attitude of non-medical staff, operational efficiency, and standardisation of medical staff.

Medical Expenses mean the amount of medical expenses spent during the whole visit.

Information Construction means online platforms and self-service equipment for patients' use.

Service Response means timely improvements per the patient's suggestions and the timely resolution of disputes.

2.2. Service quality evaluation model

The research framework (Fig. 1) was developed following the guidance in the literature. Under the framework of Donabedian's theory, six variables were subdivided into ten aspects according to tangible quality, process quality, and result quality to evaluate patient service expectations and service perceptions. The following is the logic of the theoretical framework design. As the proxy variables of tangible quality, medical environment and medical equipment are used to describe the Medical Setting. In fact, environment and equipment are the basic conditions of medical quality. For the evaluation of process quality, the authors considered service attitude, information construction, service response and medical level. Service attitude can be considered in two ways: one is for the patients and needs to focus on the service attitude of the medical staff; and the other is for the medical staff. In this study, work standardisation covers the willingness to measure staff attitudes.

Communication and service response accurately describe the information structure and service response. From the patient's perspective, the study uses the two above-described aspects to consider the efficiency of interactions between patients and medical staff. It should be noted that the medical level has three main parts. Medical level and diagnosis, and treatment efficiency belong to the category of process quality, while rehabilitation belongs to the quality of

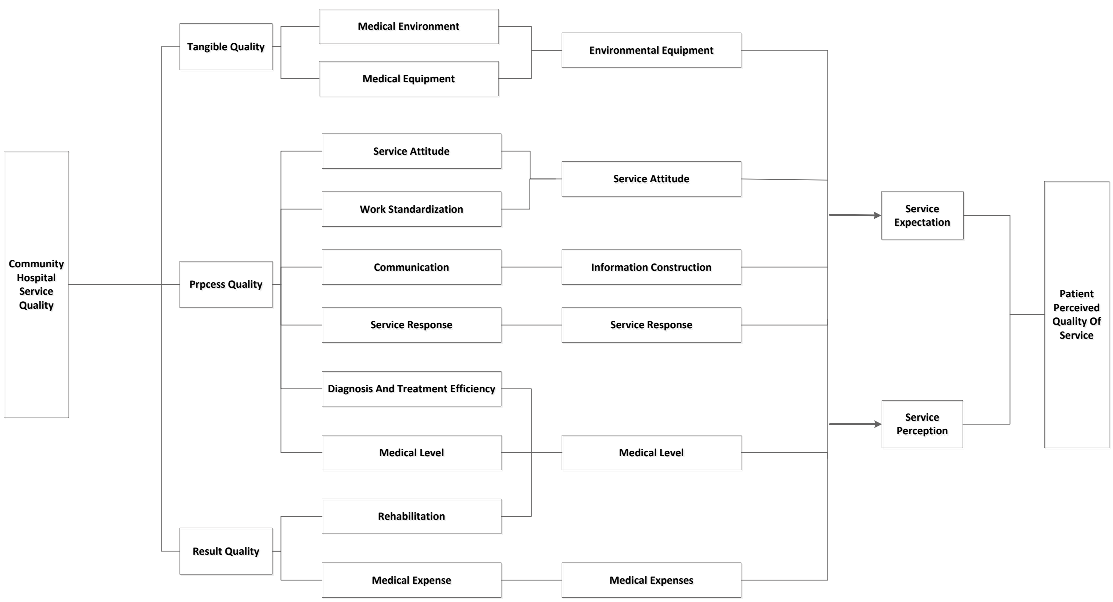

Fig. 1. Medical service quality evaluation model based on the three-faceted theory

results. Medical expenses also belong to the quality of results. The compatibility between the cost and the effect of diagnosis and treatment is considered a key factor in patient satisfaction.

This study has constructed an index system following the characteristics of the sample. It passed the robustness and effectiveness tests. Referring to the design of the quality index evaluation system for the primary healthcare service (Huang et al., 2014), in this research, the authors focused on relevant structure, processes, and outcomes in terms of service quality.

2.3. Selection principle used for the evaluation index

This paper followed the four basic principles for the design of the evaluation index system. Three principles were taken from the "O-C-W-I-S-D" approach (Peng et al., 2017), i.e., Objective, Complete, Workable, Independent, Significant and Dynamic. Also, considering that the measurement has a certain relationship with the region, the regional principle was followed.

(1) Regional principle

Based on the specific example of overpass streets, the operation of a health service centre is measured so that the evaluation indicators are targeted.

(2) Dynamic principle

The selected indicators can measure the changes of the same indicator in different periods and have practical significance over a long time.

(3) Quantifiable principle

It is better to obtain the indicators directly/indirectly through the calculation to ensure the operability of the evaluation.

(4) Hierarchy principle

Secondary indicators are established under primary indicators. Among the many secondary indicators, the indicators with strong correlation are classified and set as the same indicator group to form different levels for better analysis

2.4. Dimensions of the service quality evaluation

The service quality model SERVQUAL was divided into five dimensions: tangibles, reliability, responsiveness, assurance, and empathy. Questions were set to collect data in questionnaires, asking the respondents to score the expectation value (E) and perception value (P) for each question. The service quality score was thus comprehensively calculated using the following formula: SERVQUAL score = perception score – expectation score (Dong, 2018). Based on relevant research of JCI and KTQ, this study classified the quality of community medical service into three aspects: tangible quality, process quality, and the quality of results. The SERVQUAL scale dimensions were repurposed by the whole diagnosis and treatment process characteristics, then reranked and redivided into tangible environment quality, process quality, and result quality.

2.5. Index system for the evaluation of service quality in community hospitals

Drawing on the references in 2.4 and combining the SERVQUAL model and the three-faceted evaluation system, environment–process–result, this study constructed an index system for the evaluation of the medical service quality of community hospitals and designed a questionnaire, adhering to principles of regionality, dynamics, and quantification. In this

Tab. 1. Variables and questionnaire

Independent variable	Corresponding questionnaire questions	References
Medical settinng	1, 2, 3, 5, 17	(Hasan, 2012; Quan et al., 2018)
Medical level	6, 13, 18, 19, 23	(Al-Borie & Sheikh Damanhouri, 2013; Bowblis & Smith, 2018; Fayissa et al., 2020; Larry et al., 2002)
Service attitude	10, 11, 12, 14, 15, 16, 20, 22, 24	(Hiidenhovi et al., 2001)
Medical expenses	21, 29, 30	(Wei & Dong, 2020)
Information structure	4, 7, 8, 9	(Meng et al., 2017; Xiong, 2020)
Service response	25, 26, 27, 28	(Ayanian & Markel, 2016; Hiidenhovi et al., 2001; Robert et al., 2000)

Tab. 2. Index system for the evaluation of service quality in community hospitals

Primary Index	Secondary Index	
Objective Condition Quality	1	Good word of mouth and reputation
	2	Convenient and fast transportation
	3	Clean environment
	4	Self-service equipment operating normally
	5	Departments reasonably distributed and clearly marked
	6	Various specialist clinics
	7	Online reservation registration and electronic medical records are available
	8	Guidance on the use of medical IoT information technology system
Diagnosis and Treatment Process Quality	9	Activities propagating scientific knowledge in innovative forms
	10	The efficiency of guiding service
	11	Efficient service handling
	12	Transparent service process
	13	Alignment and referral with large hospitals
	14	Staff service attitude
	15	Communication skills of medical staff
	16	Personal privacy protection
	17	Patient flow control
	18	Personalized treatment planning
	19	Explanation of the principle of medicine
	20	Accurately recording diagnosis and treatment process
	21	Patients' trust in doctors
	22	Doctors treating patients indiscriminately
	23	Timely rehabilitation guidance
Quality of Results	24	Providing doctor consultations at home
	25	Timely return visit
	26	Establishing patients' medical records
	27	A fair settlement of doctor-patient disputes
	28	Rapid response to patients' suggestions
	29	Reasonable prescription charges
	30	Open and transparent treatment costs

Tab. 3. Evaluation criteria of the service quality evaluation system

No.	Score Range	Implication	Evaluation Content
1	SQ<-1	Much lower than expected	It shows that the service quality of community hospitals is relatively low, the overall quality is not qualified, and it demands urgent improvement
2	-1<SQ<0	There is a gap in expectations	The service quality is below the average level and unqualified
3	0<SQ<1	Meets expectations	The service quality is at the general level and qualified, but there is still much room for improvement
4	SQ>1	Higher than expected	The service quality level is excellent. It can be deemed as an advantageous programme whose high service quality should be maintained and advertised

index system, three primary and thirty secondary indexes were selected, as shown in Table 2.

2.6. Evaluation criteria of the service quality evaluation system

Drawing from research experience and exploring the application of the SERVQUAL principle in the evaluation of medical service quality, the following efforts were made in the attempt to build evaluation criteria for the service quality evaluation system (Wu & Yu, 2013). The SERVQUAL principle is based on the notion that service quality depends on the degree of difference between the service level perceived by users and the service level expected by users. The medical service quality (SQ) of Beijing's Tianqiao Community Health Service Centre equals the perception value minus the expectation value scored by patients. The quality is classified according to the SQ scores, as shown in Table 3.

A total of 211 questionnaires were collected from 107 male patients (50.71 %) and 104 female patients (49.29 %).

3. Results

3.1. Descriptive statistical analysis

The distribution of the respondents by age group is shown in Fig. 2. The proportion of respondents between 30 and 39 and 18 and 29 are the largest, accounting for 32.70 % and 30.81 % of the total number, respectively. The actual survey process tends towards the age distribution in the youth and middle-aged groups.

A relatively high proportion of patients had bachelor's degrees or master's degrees. Only 15.19 % of respondents had a high school or technical secondary school or a lower education level, indicating a relatively high level of education in this study sample. Consequently, respondents were capable of independent thinking and objectivity and fairness, which ensured the high quality of the questionnaires and the study's credibility.

The distribution of patients by occupation is shown in Fig. 3. Civil servants, staff, and entrepreneurs comprised a larger number of respondents, with most respondents (70.14 %) covered by social health insurance and 49 people (23.22 %) with commercial insurance. The portion of respondents paying for services entirely out of their pocket accounted for 6.64 %.

The survey also showed that patients chose medical institutions for different reasons. Community hospitals were selected because they are close to home and recommended by the local government. A small number of patients considered the environment of community hospitals as the factor of choice.

3.1.1. Paired sample t-test

The significant results of the survey data are shown in Table 4. The paired sample t-test by SPSS software showed that the comparison between the two was $t = 2.005$, $P = 0.046 < 0.05$, reaching a sig-

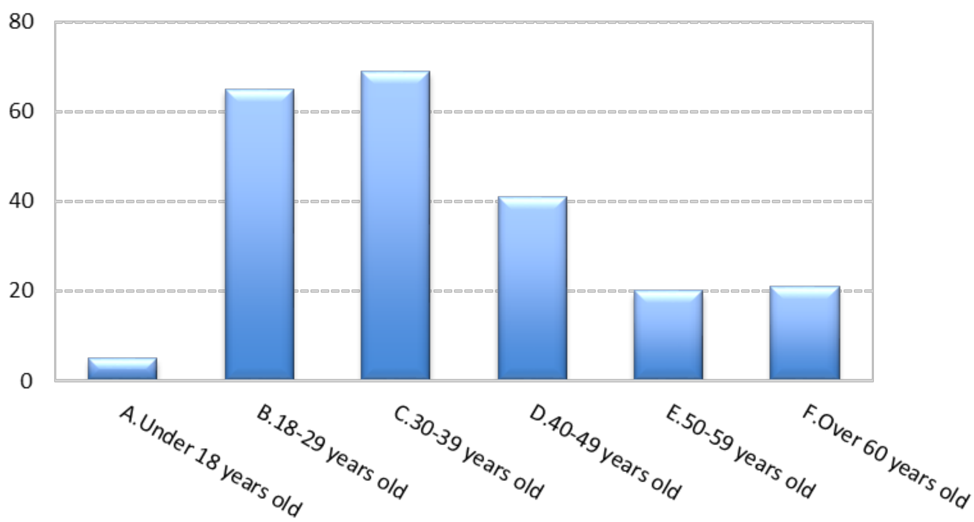

Fig. 2. Age distribution

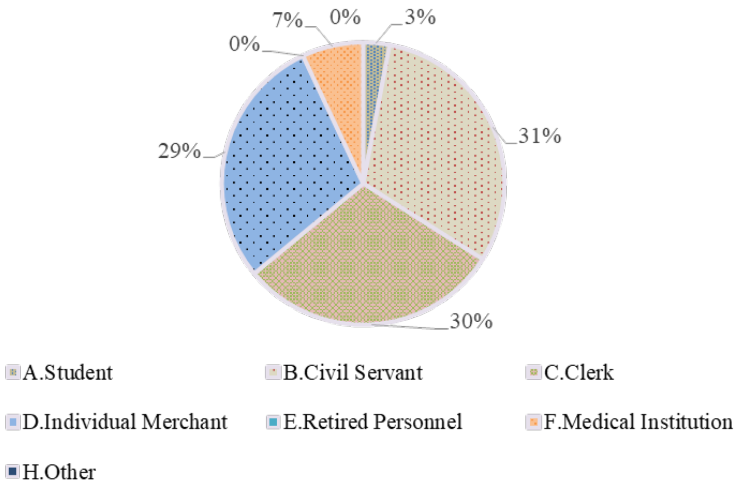

Fig. 3. Distribution by occupation

Tab. 4. Paired t-test analysis of perceived value and expectation value

Number of cases (cases)	Perceived value ($\bar{x} \pm s$)	Expected value ($\bar{x} \pm s$)	T	P
211	119.39±15.98	115.88±19.45	2.005	0.046

nificant level, and the verification results showed great differences, indicating their objectivity and accuracy.

To continue targeted discussion on the research results, it is necessary to further confirm the difference value of each facet and analyse the impact of these differences on the overall results to evaluate the overall service quality of community hospitals and the quality of different facets.

3.1.2. Mean analysis and service quality comparison of different dimensions

Through the statistical sorting of 211 valid questionnaires, this study clarified the data of 30 question items in the questionnaire (N1–N30), made a specific analysis of each facet, and used the service quality gap theory to evaluate the final results. Accordingly, a better quantitative analysis of the overall service quality could be conducted to obtain clear final results. The sample analysis of the difference between patient expectations and the perception of community hospital service quality is shown in Table 5.

As evident from Table 5, respondent expectations of the Centre's medical service quality ranged from a general to a very high level, with item N14 ("Staff service attitude") scoring the highest (4.02). This shows that patients who come to the Community Health Service Centre pay great attention to the service attitude of the staff. This conclusion is consistent with reality. On the one hand, the staff is in direct contact with the patients, and the patients have direct and strong perceptions. On the other hand, patient experiences directly affect their treatment effectiveness and follow-up visits. In general, according to the SQ values, most of the patient evaluation results of the Centre's medical service quality were higher than expected, of which 28 items were qualified, accounting for 93 %, while only two items were unqualified, accounting for 7 %. Among them were the advantages of the Centre, items with higher scores included N11 ("Efficient service handling"), N13 ("Alignment and referral with large hospitals"), and N20 ("Accurately recording diagnosis and treatment process"). The patients' actual perception scores of N5 ("Departments reasonably distributed and clearly marked") and N6 ("Various specialist clinics") were lower than expected. This result is closely related to the increasing and diversified medical needs of patients.

As shown in Table 6, the horizontal comparison of the six selected dimensions demonstrates that the importance ranking of the factors affecting the whole is in the following order (S1–S6): Service Response, Service Attitude, Medical Expenses, Information Construction, Medical Level, and Medical Setting. Beijing's Tianqiao Community Health Service Centre

Tab. 5. Sample analysis of the difference between patient expectations and their perception of community hospital service quality

Item	Perceived Service (P)	Expected Service €	Service Quality (SQ)
N1	3.85	3.81	0.04
N2	3.84	3.82	0.02
N3	3.87	3.82	0.05
N4	3.95	3.87	0.08
N5	3.81	3.83	-0.02
N6	3.91	3.93	-0.02
N7	3.85	3.76	0.09
N8	3.93	3.91	0.02
N9	3.95	3.88	0.07
N10	3.98	3.84	0.14
N11	4.13	3.89	0.24
N12	4.09	3.91	0.18
N13	4.03	3.78	0.25
N14	4.02	4.02	0.00
N15	4.02	3.86	0.16
N16	4.01	3.86	0.15
N17	4.05	3.96	0.09
N18	3.93	3.78	0.15
N19	3.99	3.82	0.17
N20	4.15	3.93	0.22
N21	4.05	3.91	0.14
N22	4.03	3.86	0.17
N23	4.05	3.9	0.15
N24	3.92	3.79	0.13
N25	4.01	3.83	0.18
N26	3.96	3.87	0.09
N27	4.07	3.87	0.20
N28	3.98	3.79	0.19
N29	4.00	3.95	0.05
N30	3.96	3.82	0.14

Tab. 6. Scores and sq values of various dimensions of medical service quality evaluation indexes

Index	Perceived Service (P)	Expected Service (E)	Index SQ
S1	3.85	3.88	0.03
S2	3.84	3.98	0.04
S3	3.89	4.04	0.15
S4	3.89	4.00	0.11
S5	3.86	3.91	0.05
S6	3.84	4.00	0.16
R	3.85	3.88	0.03

is recognised by patients in terms of staff attitude and improvement; however, its environment and medical level remain inadequate. These conclusions are consistent with the self-positioning and limited medical level of the Centre.

3.2. SWOT analysis of medical service quality

SWOT analysis is a tool for situation analysis. The SWOT analysis of the medical service quality of the Beijing's Tianqiao Community Health Service Centre further clarified the advantages and disadvantages of the Centre's medical service quality and the opportunities and limitations of its future development. The results are as follows:

Advantages: High service level and qualified rate. "Efficient service handling", "Alignment and referral with large hospitals", and "Accurately recording diagnosis and treatment process" received high scores. The Centre may fully emphasise these advantages to ensure that these three items continue to maintain at a high level in the following improvement process and continuously improve the service level. At the same time, located in the community, the Centre can attend to the general medical needs of the community effectively.

Disadvantages: Third-level hospitals are the main medical resource in the region, including more scientific department design, advanced and expensive medical equipment resources, etc. China's medical system is undergoing reform. The time for the establishment of a community health service centre is relatively short. Also, due to the limitation of technologies and equipment, the overall service quality is still relatively low. The available equipment and the environment are inadequate, which limits the rapid improvement of service quality.

In addition, due to the small number of patients, the setting of departments is not standardised, and the direction signs are not sufficiently clear, which contributes to patients' negative medical experiences to a certain extent. Some patients lack information, fail to use self-service devices or talk to medical workers via WeChat groups or other online channels, as they are unwilling to disclose their medical problems. Therefore, information services fail to be fully utilised, and the efficiency and effect of the treatment can be compromised.

Opportunities: The visit identified difficulties for the public to access a doctor. On the one hand, patients attach great importance to their health. They hope to go to the top three hospitals if they have any problems, resulting in seriously uneven resource allocation. On the other hand, the overall development of intelligent medical services is relatively backward.

Many patients cannot make timely appointments or have consultations online, resulting in a negative experience. It explains the low loyalty of residents to the Centre and higher expectations for the medical service quality.

Threats: Some local highly educated medical graduates and experienced medical specialists would seek longer careers in academic research, senior professional ranks and titles. They are more inclined to work in class III hospitals. The technical, diagnostic and treatment level of community health service centres fails to meet patient needs, which reveals the lack of talent in grass-root medical institutions. Information provided by the Centre's manager explained difficulties in the recruitment and retention of medical staff. Most medical specialists have a bachelor's degree, and there is a serious shortage of medical staff with higher professional titles. Consequently, patient expectations are low, and many potential customers choose other hospitals for treatment.

4. Problem analysis

The third part, which was a preliminary proof of hypotheses 1 & 2, was unlike all previous studies. The authors found that patient expectations for the Community Health Service Centre were below the realistically available standard, and inadequate medical environment, hardware equipment, and medical level are more important factors than patient expectations. From 1 July 2021, insured urban and rural residents of Beijing can use all designated community health service institutions in Beijing as their first outpatient medical care facilities for services (Sina.com, 2021).

On the one hand, due to COVID-19, patients are willing to go to a community hospital when they are not suffering from serious diseases to reduce the risk of infection. On the other hand, to help the public and reduce the pressure on class III hospitals, the government made intense investments in the development of community hospitals, and patient satisfaction has been improved. As more patients opt for community hospitals, requirements grow to have more diverse departments and specialist clinics.

4.1. Problems

Despite the substantial role of community health centres in local populations and the broader safety-net healthcare system, very limited research has been conducted on community health centre research experience, infrastructure, or needs from a national perspective (Sina.com, 2021; Beeson et al., 2014).

(1) Sometimes, the results of diagnosis and treatment fail to satisfy patients and customers.

About 1 % of surveyed patients indicated that diagnosis and treatment results of community hospitals failed to meet the expectations due to technical issues, such as wound sutures that were too visible.

(2) Medical services sometimes take a long time to complete.

Individual customers indicated the failure to successfully receive the test or injection for themselves or their children during one visit to the community hospital. They needed another intervention or several procedures, which wasted time and affected the service experience. Also, patients wanted to be served by more qualified medical staff.

(3) Lack of a complete service recovery system and streamlined service process.

Some customers said that the community hospital could not give the customer a relatively satisfactory explanation and implement positive remedial measures in the case of customer dissatisfaction caused by its improper operation.

(4) Insufficient use of Internet technologies.

The existing information system is relatively weak, utilising only the basic LIS, RIS, and EMR systems. It supports the functions of WeChat and Alipay's recharge query report or the hospital information based on the basic functions. In terms of management, there is no partial management software such as OA office automation, medical record management system, hospital experience system, and clinical pharmacy to conduct information-based management of the hospital's situation, which is semi-manual and semi-information-based. Hospital information structure fails to keep up with modern medical development.

Due to the need for epidemic prevention and control of COVID-19, patients need to scan three codes when entering the hospital, including Jiankangbao, Hospital Information Registration Form, and a Travel Itinerary. These requirements are unfriendly to elderly patients without smartphones and living alone, making them feel uneasy about going to community hospitals.

4.2. Analysis

4.2.1. Professional level of medical staff needs improvement

Medical staff often make mistakes during interventions. Some patients indicated that medical staff failed to complete interventions, such as sticking a needle and blood drawing, from the first attempt. Others specified that medical staff failed to handle the wound properly during suture, resulting in inflammation at a later stage or prominent scarring. Respondents also believed that outpatient doctors and surgeons failed to make effective judgments in time for some emergencies.

4.2.2. Systems should be developed for regular evaluation of medical service level and staff training

Failure to establish systems for regular evaluation of the service and staff training is among the key reasons for the insufficient skills of medical specialists and the low speed of technological improvement.

4.2.3. More attention should be given to the service recovery system

Attention should not only be given to the medical setting of facilities but also to their service recovery systems. Service quality evaluation is becoming popular among the patients of community hospitals. It should be considered that patients satisfied with their diagnosis and treatment give a high score, while customers with a less smooth process of medical treatment tend to give a negative evaluation.

4.3. Conclusions and recommendations

In conclusion, the Community Health Service Centre has encountered difficulties and problems, such as low patient expectations, a negative media environment, inadequate equipment and a low medical level. Proceeding from the Centre's actual condition, the following suggestions are made to improve its medical service quality.

First, strengthen publicity. On the one hand, to expand the scope of offline publicity, community health service centres should actively cooperate with local communities and residents' self-governing organisations for promotion and popularization, using the advantages of their specialist clinics and characteristic activities. On the other hand, community health service centres should optimise online publicity platforms. They may set up clear and easy-to-read signs, simplify procedures, adopt online registration, and cooperate with the medical service platforms often used by residents, such as JingYiTong and 114 Health. These methods can make registration more convenient. Patients' needs for health knowledge can be satisfied by setting up online resources to propagate scientific knowledge to special groups, thus forming a benevolent interaction with residents. Strategically aligning nurse shifts to demand is also an effective approach to meeting client needs without increasing total nurse staffing levels in a community health centre context (Merino et al., 1982).

Second, improve the medical environment. Community medical services mainly refer patients with different degrees of illness and undertake the first diagnostic function. However, due to a high flow of patients, community medical services failed to meet residents' basic needs, and relevant medical facilities still need to be strengthened (Yuan, 2020). According to Marshall, early planning measures, the focus on community needs and formed strategic partnerships can provide a valuable foundation for future events aimed at boosting community engagement in public health efforts (Samantha et al., 2021). The main reasons patients avoid choosing this Centre are the lack of available departments, the inadequate qualification of doctors, and the fear of poor treatment results. Therefore, the Centre must improve medical service quality. (1) In terms of the hospital's layout, the location of departments should be reorganised and guiding signs should be placed reasonably according to medical procedures, making patients walk less to improve the overall experience in the hospital's environment. (2) In terms of equipment and facilities, community hospitals should actively seek to adopt state-of-the-art technologies considering their relatively small space. To improve patient satisfaction, boost the hospitals' relevance and support their long-term development ambitions, community hospitals should also implement strict procedures for technology upgrades and inspection. The focus on community needs and strategic partnerships can provide a valuable foundation for future events aimed at community engagement in public health efforts.

Third, promote medical techniques. As the mainstay of medical service is medical professionals, staff training becomes the key to improving medical service. (1) Intensify the development of a well-trained workforce, improve the quality and professional competence of medical workers, and enhance their medical techniques. (2) Particular attention should be given to general medical practitioners. More specialised departments should be established, continuously enlarging the scope of medical diagnostics and treatment. (3) Create a learning atmosphere, encourage medical staff to pursue further studies, professional titles, qualification certifications, etc. (4) Take full advantage of the geographical location, actively cooperate with large hospitals for opportunities to learn, hire external experts, etc.

Fourth, accelerate the application of information technology (IT). Replace the workforce with IT applications to improve efficiency. Against the backdrop of the COVID-19 pandemic, information technologies can reduce the physical flow of people, enable the use of early warning systems for infectious diseases in hospitals and promote IT-based management systems. Establish specialised IT, recruit qualified staff, undertake timely inspection of equipment, and ensure training for medical workers to ensure the appropriate operation of equipment. Implement various forms of appointment diagnosis and treatment services via telephone, network, WeChat, and on-site booking.

A WeChat official account or a cell phone application can be set up to provide online booking, payment, and follow-up services to reduce waiting time and effectively divert patients to the doctors. Promote Internet Plus healthcare. Use cloud computing, big data, mobile Internet applications, and other technologies to achieve unified data management, improve patient treatment experience, realise health information integration, and promote the development of the hospitals. Utilise mobile Internet, reengineer operation management and service process to improve management efficiency and service level.

Fifth, establish patient complaint mechanisms and channels. Full understanding and active solving of medical service complaints are effective means to continuously improve the medical service quality and an important way to maintain harmonious doctor–patient relationships. Hospitals should establish feasible complaint mechanisms and channels to timely deal with various problems raised by patients. Considering patient flows, hospitals may take patient suggestions by establishing special complaint reception offices, building online platforms to post comments, or other ways, based on existing channels of telephone complaints, random telephone return visits, etc., to ensure that medical disputes are handled as soon as possible, and medical service quality is improved.

Sixth, the Centre should care for its medical staff and raise their salaries. A post-performance appraisal and incentive system should be established with service quality at the core to encourage the medical staff. Personal development for medical professionals should be planned, providing training and promotion opportunities. Other measures should also be considered, including a good working environment, logistic support and improved social status of medical workers. If possible, community volunteers should be recruited to help the elderly seek medical treatment. Also, the government can facilitate the interactions between the medical school and the community (Marshall et al., 2021).

5. Discussion and implications

By taking Beijing's Tianqiao Community Health Service Centre as an example and using Donabedian's structure–process–outcome theory and the SERVQUAL evaluation scale to construct an evaluation model, the study closely followed the direction of medical reform and integrated intelligent medical care into the evaluation of medical service quality. After analysing the data collected by a questionnaire survey, specific measures for the improvement of services were proposed, also providing a new research idea for studies on the improvement of medical service quality.

Three research questions were examined in this study: (1) How to build an index for the evaluation of medical service quality to achieve both process quality and the quality of results? (2) Does the quality of medical service affect patient decisions? (3) What are the problems encountered by community health service centres in China? Using a sample of data from Beijing's Tianqiao Community Health Service Centre, we found direct associations between medical service quality and patient decisions (H1 supported). Patient expectations for the Community Health Service Centre were below the realistically available standard, and inadequate medical environment, hardware equipment, and medical level are more important factors than patient expectations (H2 supported).

In terms of theoretical implications, this study makes several contributions to service quality research and practice. It contributes to the advancement of the theoretical framework of Donabedian's structure–process–outcome theory and the SERVQUAL evaluation scale in the Chinese context and the application of quality management theory in the field of medical service quality management. Also, it provides definitions, measurements, principles and ideas for how to construct the medical service quality evaluation system. This research effort also contributes to suggestions for the improvement of medical service quality. This study filled the gap left by previous studies, which often focused on the "outcome" but lacked the evaluation of "structure" and "process".

In terms of managerial implications, the effectiveness of quality evaluation results is often affected by various factors. This study measured the evaluation results of the index system which was designed. Measurement results and SWOT analysis were used to determine the advantages, disadvantages, opportunities and threats of Beijing's Tianqiao Community Health Service Centre. Six main suggestions for improving the quality of medical services were formulated, including strengthening publicity, improving the medical environment, promoting medical techniques, accelerating the adoption of information technologies, establishing patient complaint mechanisms and channels, and caring for medical staff by improving their salaries.

Limitations were encountered due to the recurrent outbreaks of COVID-19 at the time of questionnaire distribution. Consequently, the elderly group who use smart devices less actively was not included. In the future, the authors plan to conduct in-depth research on the construction of intelligent medical care and study the integration and practice of IT applications and patients.

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Role of remote transformational leadership on service performance: evidence in Indonesia

Muafi Muafi Ahmad Johan

ABSTRACT
This study examined and analysed the role of remote transformational leadership in business strategy consensus by considering the contingency of competitive intensity and organisational learning culture. The population of this study are owners or service managers of start-up business companies in the provinces of DIY and East Java. The sampling technique used was a purposive sampling method with a sample size of 231 managers. The data was collected through the distribution of questionnaires and interviews with several key service managers who represent their companies. Euclidean Distance Simple Regression and Euclidean Distance Simple Regression Moderation were used as the statistical processing tools. The results of this study proved a fit between each business strategy typology with each contingency variable examined in this study. It was also found that transformational leadership could strengthen the relationship pattern. The contingency approach is crucial because situations and conditions between organisations may vary depending on the company's internal (organisational learning culture) and external (competitive intensity) environment, especially in the era of the Covid-19 pandemic. Contingency fit in the organisational strategy needs to be assessed so that the service performance can be improved and sustainable in the long term. This situation and condition will improve when strengthened by the role of remote transformational leadership.

KEY WORDS
competitive intensity, organisational learning culture, remote transformational leadership, service performance

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Muafi Muafi

Universitas Islam Indonesia, Indonesia
ORCID 0000-0002-5078-4670

Corresponding author
e-mail: muafi@uii.ac.id

Ahmad Johan

Sekolah Tinggi Ilmu Administrasi
Bandung, Indonesia
ORCID 0000-0003-1251-6728

Introduction

Undeniably, the Covid-19 pandemic positively affected several start-up sectors, particularly payment systems, logistics, agriculture, and health. On the other hand, the tourism, e-commerce, and maritime sectors were severely hit (cohive.space.com, 2021). Most populations in these business start-ups are millennials with a high digital presence, even though some have only entered cyberspace for the first time (Kriswinanto, 2020). The Province of DIY and East Java, Indonesia,

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are two ideal areas to start an Internet-based business or a digital start-up. The provinces provide supporting ecosystems that can make and help digital start-ups thrive, such as creative centres, co-working spaces, and business incubators (Kriswinanto, 2020; cohive.space.com, 2021). The growing demand for private offices and reduced demand for open workspaces indicate the increasing need for remote work. Even so, the need for co-working spaces will still be a good choice for those who want to work remotely and have virtual meetings (cohive.space.com, 2021). The current toughest challenge for start-up businesses is the presence of several big players whose performance continues to move up, balanced with the ownership of technology, human resources, good leadership, and management. Various inventions over the past few decades, such as mainframes, PCs, Internet, mobile technologies, cloud computing, AI, user interface (UI), and communication solutions, have succeeded in increasing productivity and becoming innovation forerunners. This study focused on discussing competitive intensity and organisational learning culture that impacts business strategy and service performance, especially for small and medium start-up businesses.

Each start-up business competes to retain its customers. To attract new customers, they introduce several new product features with all the advantages and benefits of their products and services. Due to the spread of Covid-19, currently, start-up businesses are increasingly directing their activities to be digital. Optimising the digital system is considered a necessity in facing the challenges of the start-up world amid the Covid-19 pandemic.

To compete successfully, digitalisation is the main choice besides changing the mindset to continue to create synergy and innovation, including leadership. In this regard, remote transformational leadership is an important and crucial aspect so that the managed start-up business can run according to the company's vision and mission, especially when it is related to competitive intensity and organisational learning culture. All of this will impact service performance amidst the increasingly rapid and uncontrollable business digitalisation.

Limited studies have been conducted on the moderating role of remote transformational leadership associated with the contingency of competitive intensity and organisational learning culture that require business strategy consensus with a contingency approach in the start-up industry. This served as a motivating factor to undertake the present study and became its originality. More details are given below:

- Based on empirical evidence, it is widely accepted that with the Environment–Strategy–Performance (E-S-P) approach, the internal and external environmental aspects can have a strong relationship pattern with business strategy and organisational performance. However, in general, the findings tend not to use a contingency approach which ultimately cannot recommend the level of fit of business strategies that have an impact on organisational performance.
- The start-up industry is required to be able to adapt contingently to its external (competitive intensity) and internal (organisational learning culture) environment, in which organisational performance is required to exceed the level of an average competing company.
- Business strategy uses a typology of innovation and imitation strategies with a contingency approach. This business strategy must be chosen by the start-up industry to deal with the unpredictable and uncertain situation of the Covid-19 pandemic.
- The Covid-19 pandemic requires a remote transformational leadership role that is visionary and transformative by being able to take advantage of agile information technology.

The above-mentioned gaps motivated this study to explore the best business strategy to be applied in achieving service performance in the context of start-up business in two Indonesian provinces using a contingency approach. This study considers the contingency of competitive intensity and organisational learning culture to provide information and suggestion for the level of fit of a business strategy. Furthermore, this study also employs the variable of remote transformational leadership as the antecedent of business strategy and performance to adjust to the changing condition and digital trends in a business context. It is expected that this study can contribute to the start-up business practice by suggesting the appropriate strategy that is adjusted to the condition of competition (competitive intensity) and their organisational learning culture.

2. Literature review

1.1. Competitive intensity and business strategy

The classical industrial organisation literature believes that company behaviour is limited by the strength of an industry (Bain, 1956). This view continues to evolve and is finally renewed by some of the findings from Porter (1979; 1980; 1985; 1990) by considering studies in the corporate context; hence, some of his findings demonstrated that industrial structure is largely influenced by company activities. Porter's views (1979; 1980; 1985; 1990) regarding the industry's impact on companies faced many challenges considering the intensity of competition and industry structure. Porter emphasised (1979; 1980; 1985; 1990; David, 2011) that competition is the core of success, and even a company's failure is subject to competitors feeling the pressure or seeing an opportunity to maintain their position above the average competitor company. Competitive intensity is a function of several factors, including industry concentration, barriers to exit, barriers to entry, demand conditions, and product characteristics (Porter, 1980; Hill, 1992). Hill (1992; Porter, 1980) divided typologies into two; benign and hostile. A benign competitive environment is characterised by strong demand, substantial entry barriers, high industry concentration, non-commodity products, and focused on non-price factors, such as advertising, design, quality, and service. On the contrary, a hostile competitive environment is characterised by weak demand, high exit barriers, high fixed costs, commodity products, and low industrial concentration. The combination of these factors may lead to price wars and cost reduction. Homburg et al. (2002) added that competitive intensity could be one of the most important factors in corporate strategic decision-making. Companies can pay attention to the external and internal environment that has been managed so far. When a company is faced with a very tight competition situation, it is advisable to adopt a service-based business strategy to increase customer value (Gronroos, 1997) and strengthen customer relationships (Homburg et al., 2002). Dess and Davis (1984) concluded that industrial competitive intensity could, directly and indirectly, affect company performance. Similarly, other studies also confirmed that industrial competitive intensity could significantly improve company performance (Estrada-Cruz et al., 2020; Tiantian et al., 2013; Al-Rfou, 2012; Hoque, 2011; Chen, 2010). However, other findings have concluded that industrial competitive intensity cannot improve company performance (Teller et al., 2016; Assaf & Cvelbar, 2011; Fosu, 2013). This can occur due to the emergence of new competitors and the existence of substitute products and price competition. On the other hand, there are also other factors that need to be considered in improving organisational performance, namely competitive intensity and type of competition. The research results from Chen et al. (2015) provided empirical evidence that these two dimensions of competition have an impact on the use of incentives for non-financial performance measures. This means that performance measurement does not only consider financial aspects (Chen et al., 2015). Developing a business certainly requires an optimal, consistent, and continuous effort. The high intensity of business competition during the Covid-19 pandemic certainly continues to force and demand business actors to develop business strategies so that the business developed can grow well and succeed.

On the other hand, O'Brien (2003) found that innovations negatively affect organisational performance because of large spending on research and development. However, it is generally expected that a correctly and maximally implemented business strategy will achieve success. Several studies have shown that innovation strategies can improve organisational performance (Calantone et al., 2002; Jin et al., 2004). A passive manager always assumes that competitive intensity is benign, with a safe and easy-to-control business environment. This attitude makes them somewhat passive in scanning the environment and inclined to wait for an outside signal, and vice versa (Day & Schoemaker, 2006). It is suggested by Hitt et al. (2001) that managers should increase their knowledge about competitive intensity because it will be able to provide an understanding of increasing the company's competitive advantage. Estrada-Cruz et al. (2020; Robertson & Chetty, 2000; Covin & Slevin, 1991) concluded that when a company is faced with high/hostile competitive intensity, the company will choose entrepreneurial/innovative strategies so that business performance increases. Explorative innovation will be carried out when companies face tight market turbulence, so they must utilise resources effectively (Estrada-Cruz et al., 2020; Wang & Ke, 2016) and vice versa. In this regard, the imitation strategy is effective when the pioneer conditions are not profitable and not necessarily able to create a sustainable competitive advantage (Wanasika & Conner, 2011). Companies can creatively generate imitations by absorbing existing knowledge to produce something new, which can also be used to create unique products and services (Assavapisitkul & Bukkavesa, 2009).

H1. The higher the degree of fit between imitation strategy and benign competitive intensity, the more the service performance will be improved.

H2. The higher the degree of fit between innovation strategy and hostile competitive intensity, the more the service performance will be improved.

1.2. Organisational learning culture and business strategy

An organisation's business continuity is determined by its ability to maintain its operations. Market competition demands that companies have more advantages over their competitors. The rapid development of the market must be balanced with the knowledge that exists in the company. Companies must continue to improve their performance to meet consumer demands by maintaining quality and innovating with their products through knowledge. Therefore, improving and enhancing organisational capabilities must be continuous and based on a learning process. Hence, organisations are required to be learning organisations through continuous learning, employee empowerment, strengthening of embedded systems, and sharing and discussing such important aspects as means and collective values (Islam et al., 2015; 2016).

Organisational learning in a company will become its culture if it has become a habit and is passed down from one generation to another, carried out continuously. New company employees can follow previous staff members in carrying out organisational learning (Škerlavaj et al., 2010; Murray & Donegan, 2003). This is also a reflection to improve the quality of the organisation to win the competition. Organisations that practice learning are adaptive, flexible, and able to improve organisational performance through individual learning (Islam et al., 2015; 2016). Islam et al. (2015; Škerlavaj et al., 2010) studied learning organisations from a cultural perspective and named the phenomenon the organisational learning culture (OLC). Islam et al. (2016; Škerlavaj et al., 2010; Dimovski, 1994) explained that OLC could be characterised as an organisation skilled in creating, acquiring, transferring knowledge, and modifying behaviour to reflect new knowledge and insights. They mentioned that OLC could influence the company's contextual performance. Furthermore, other findings confirmed that organisational learning could improve long-term sustainable performance so that employees are ready to assume additional responsibilities outside of their formal duties (Islam et al., 2015; 2016). In a similar vein, the study conducted by Škerlavaj et al. (2010) concluded that OLC could improve innovation performance in the long run.

This study refers to the typology of the organisational culture model "The Competing Values Framework (CVF)" introduced by Cameron & Quinn (2011; 1999; Quinn & Cameron, 1988), namely, clan, hierarchy, adhocracy, and market culture. Hierarchy and adhocracy strategies are very suitable for the contingency approach because the two typologies fit imitation and innovation strategies. Several studies have proven that organisational culture can improve organisational performance (Chen et al., 2018; Zwaan, 2006; Vestal et al., 1997). When companies implement an adhocracy culture, the organisation must have an orientation towards innovation and creativity (Valencia et al., 2010; 2016; Martins & Terblanche, 2003).

On the contrary, Xu and Qianqian (2015) found that organisations using an imitation strategy tend to implement a hierarchical culture. Also, Priyono (2004) added that an organisation with the Apollo organisational culture (bureaucracy and discipline) would tend to implement a defender strategy. On the other hand, an organisation with the Athena organisational culture (innovative and proactive) would tend to implement a prospector strategy. In Indonesia, organisational culture (Apollo, Athena, and Clan) can become the basic philosophy to provide direction for organisational policies in employee management (Nasution, 2019; Santoso, 2005). This means that when a company has an adhocracy OLC, it should have an innovative strategy orientation. Conversely, when a company has a hierarchy OLC, it should have an imitation strategy orientation. It should be noted that characteristics inherent in the imitation strategy are as same as defender/cost strategy. On the other hand, the characteristics inherent in the innovation strategy are as same as the prospector/innovation strategy.

Khurosani (2013) supported the previous findings on a strong relationship pattern between adhocracy organisational culture with cohesive freedom value, learning commitment, and leader's work creativity. Also, Wei et al. (2014) confirmed that the organic/adhocracy culture could influence market responsiveness so that it can increase superior company performance that varies in various types of industries.

H3. The higher the degree of fit between the imitation strategy and the hierarchy OLC, the more the service performance will be improved.

H4. The higher the degree of fit between the innovation strategy and the adhocracy OLC, the more the service performance will be improved.

1.3. Innovation vs imitation strategy

Strategic issues that currently concern academics and practitioners are innovation (Carol & Mavis, 2007; Sánchez et al., 2011; Bakan & Yildiz, 2009) and imitation (Wanasika & Conner, 2011; Lee & Zhou, 2012; Assavapisitkul & Bukkavesa, 2009). Innovation strategy is believed to be a key factor in increasing company growth (Senge & Carstedt, 2001) and competitive advantage in the future (Kiarie & Lewa, 2019). A company with innovation has to enrich and expand its innovation orientation by optimising its current resources to improve individual and organisational capabilities. It is important to realise the competitiveness of its products and services compared to the competitor (Bloodgood, 2013; Kuhn & Marisck, 2010; Ming-Chao & Ke, 2016). The results of several studies reinforce the statement that the role of innovations is indispensable in creating company performance (Kiarie & Lewa, 2019; Suhag et al., 2017; Mafini, 2015). Daft & Marcic (2005) added that organisations choosing an innovation strategy actually intend to create or produce new forms and are expected to have an impact on employee behaviour.

This study refers to the Theory of Organisational Cognition and Learning, in which organisations adopt new ideas that aim to solve problems and find solutions. The emphasis lies on the learning process and the utilisation of individual cognition in the innovation process. This condition will occur when there is a learning process and good knowledge management in the organisation to analyse the organisational capacity and employee capabilities. Furthermore, in an organisation, knowledge needs to be managed effectively and innovatively (Darroch, 2005). Rehman et al. (2019) also added that there is a positive relationship between organisational learning and organisational performance. When new knowledge is acquired and learned through a continuous learning process, it will lead to the development of innovative ideas. If this condition occurs, it can be used for the purpose of introducing new things in addition to the existing ones so that they can come up with new ideas to innovate (Byukusenge et al., 2016; Al-Suradi et al., 2016).

On the other hand, the imitation strategy is a process that can be carried out as a supporter of the desired innovation (Enkel & Gassmann, 2010). Shenkar (2010; Schnaars, 1994) stated that a person could learn, feel, survive, compete, and develop slowly when they have positive traits and behaviours as a result of interactions with their environment. This can be done by imitating or copying the behaviour of others. Schnaars (1994) even suggested that this behaviour is common in the business world with the late entrant market. The imitator company can enter the market by following the market of the innovator company. They offer the same products and services. Another strategy is that imitator companies act as pioneers, namely, entering the market first by offering the same products/services but at a lower price.

In general, imitation strategy combines three strategies, namely (Filianty, 2013), (1) lower prices compared to the pioneer products, (2) selling a superior product compared to pioneer products, and (3) using their market power to overwhelm the weaker pioneer by directly attacking those at a weak position. A lower price strategy is feasible since imitators do not require costs for market research and have low promotional costs. Furthermore, Dhewanto et al. (2015; Hasnin, 2016) added that the imitation strategy could be profitable because of its low selling price, market education, risk of product failure, and research and development budget.

1.4. Moderating role of remote transformational leadership

Several studies have proven that leadership in Asia and Europe has become a strategic issue that can strengthen the influence of contingency variables on organisational performance (Son et al., 2020; Muafi & Kusumawati, 2020; Ximenes et al., 2019; Yeh et al., 2016; Pongpearchan, 2016; Muafi et al., 2020; Sari, 2018; Hutagalung, 2016). Transformational leadership theory has been used as one of the theories to understand leaders' effectiveness in the last two decades (Li & Hung, 2009; Piccolo & Colquitt, 2006). A meta-analytic study from Lowe et al. (1996) reviewed 39 studies from various countries and concluded that transformational leadership is particularly effective in improving organisational performance. Leaders must be able to influence their employees, and employees are expected to be willing to work together to achieve organisational goals (Bass, 1998; 1985) and able to achieve goals that have never been achieved before (Locke & Latham, 2002; Locke et al., 1988; 1981). Bass (1998; 1985) added that transformational leadership must encourage trust, respect, and admiration from its followers and have a high commitment and motivation to achieve. Avolio et al. (1999) also stated that transformational leadership should also improve the relationship between leaders and followers more closely; therefore, it is not just a job agreement, but it is more based on trust and commitment. Bass (1998) introduced the term "Four I's", namely, individualised influence, inspirational motivation, intellectual stimulation, and individualised consideration. Individualised influence means that followers identify and demonstrate behaviour that exceeds the standards set by the leader in terms of performance, values, ethics, and morals. Inspirational motivation means that leaders provide enthusiasm, commitment, and high expectations to followers. Intellectual stimulation means that leaders find new ways by using past approaches. Individualised consideration means that leaders serve the employee's needs for organisational performance improvement.

In the current era of the Covid-19 pandemic, a disruption in human resources functions has become apparent, starting from recruitment and selection to compensation and company leadership. Several changes must be inevitably implemented in strategies, policies, and guidelines, especially on the way of work, interaction, communication, and leadership. This is done to reduce the spread of the virus that is getting out of control. All citizens, including those in Indonesia, must comply with health protocols to reduce the spread of Covid-19. In Indonesia, the Covid-19 pandemic significantly negatively impacted the education, business, government, community, and media sectors. Businesses categorised as vulnerable faced the highest threats leading to increased unemployment and poverty and decreased number of economically capable people (Hidayat, 2020; Utomo, 2020; Mungkasa, 2020; Nasution et al., 2020). Ramadhani (2020) revealed that 78 % per cent of employees who work from home (WFH) could still be productive, so this type of work could continue in the long term until Covid-19 can be controlled. WFH has its own advantages and disadvantages with all problems that arise and impact the company's performance (Mungkasa, 2020).

The strategic aspect that is currently challenging is the leadership role in the era of the Covid-19 pandemic. Leaders are required to be able to plan, organise, mobilise, and evaluate employee performance without having to meet face-to-face because it can be done through remote leadership (Kelley & Kelloway, 2012). According to Kelley & Kelloway (2012), the concept of remote leadership can be used to minimise physical and face-to-face interaction with employees, and instead, it can be done through information technology as measured by regularly scheduled communication and unplanned communication. Kelloway et al. (2013) also found that remote transformational leadership can improve informational justice, satisfaction, and motivation of student participants as the messages can be received well because of the intellectual and charismatic characteristics of leaders manifested in the way they give orders and write emails. Lilian (2020) added that organisational success relies heavily on the knowledge of leaders about the effect of information and communication technology on teamwork to manage leadership challenges in virtual world management. The results of the study concluded that the combined influence of the interaction between transformational leadership and competitive intensity could improve company performance (Yang & Yang, 2018). Ximenes et al. (2019) also supported the findings that entrepreneurial leadership can strengthen high-performance work systems and employee creativity on organisational performance.

Facing increasingly fierce business competition, the start-up industry in Indonesia must improve its service quality. Low service quality drives customers to higher-quality competitor services. Service quality is measured based on the perceived performance of a service received by customers and is better known as the SERVPERF (service performance) model (Cronin & Taylor, 1994; 1992). Cronin and Taylor (1994) used five service performance or SERVPERF indicators, namely, time, accessibility, completeness, courtesy, and responsiveness, with service performance perceived based on the actual and not on expected performance (Dimitriades & Maroudas, 2007). They also suggested five dimensions of service performance or SERVPERF be used in general by service companies in measuring the service performance level. Cronin & Taylor (1992) examined the SERVPERF model in four industries, namely, banking, pest control, dry cleaning, and fast food. It turns out that the SERVPERF model can explain the actual customer's perception of service performance.

Brady and Cronin (2001) added that customers form service quality perceptions based on the evaluation of service performance at various levels. Furthermore, they combined the results of their evaluation into their perception of the overall service quality. Alford and Sherrell (1996) stated that service performance could be a good predictor of service quality received by customers aiming for increased customer loyalty. This study focuses on the perceived service performance of start-up business owners and managers using the SERVPERF indicator from Cronin and Taylor (1992), in which the performance of start-up

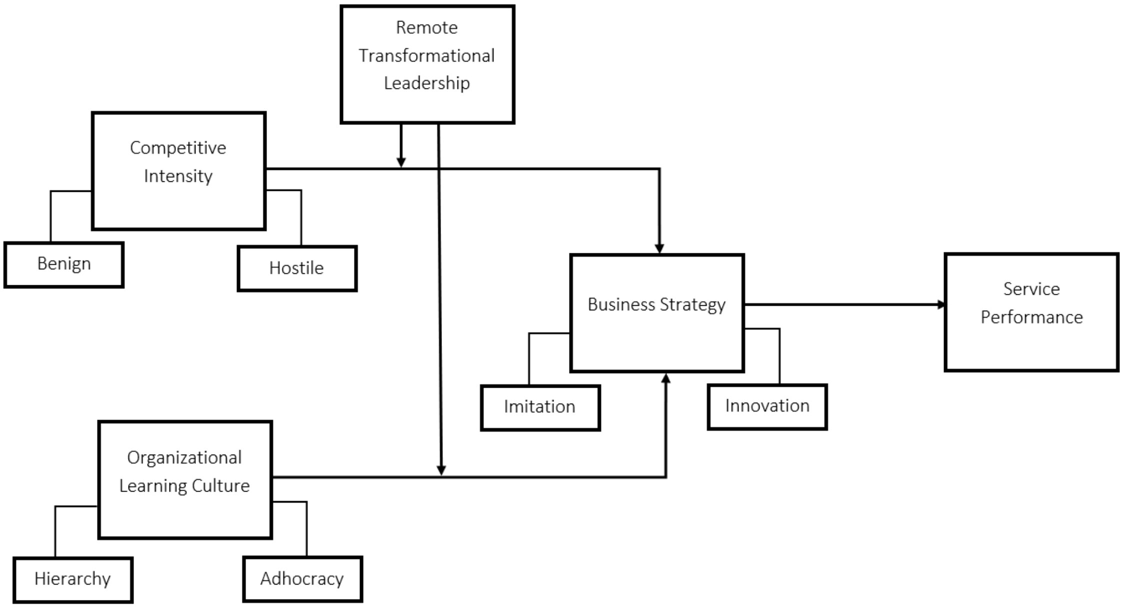

Fig. 1. Research model

businesses is measured from non-financial performance compared to similar companies in the last five years.

H5. Remote transformational leadership can moderate by strengthening the fit relationship of the imitation strategy having the benign competitive intensity with the service performance.

H6. Remote transformational leadership can moderate by strengthening the fit relationship of the innovation strategy having the hostile competitive intensity with the service performance.

H7. Remote transformational leadership can moderate by strengthening the fit relationship of the imitation strategy having the hierarchy OLC with the service performance.

H8. Remote transformational leadership can moderate by strengthening the fit relationship of the innovation strategy having the adhocracy OLC with the service performance.

2. Research methods

This study followed a positivist paradigm based on the belief that empirical reality has value-free testing. This is because reality is single, real, divisible, and focuses on causality. This type of study uses a survey, and the data is collected through questionnaires and interviews with several key respondents (Lutz, 1989).

The population of this study comprised owners or managers of start-up businesses in two provinces, namely, Special Region of Yogyakarta (DIY) and East Java. This study used the sampling technique of purposive sampling with the following criteria: (a) service managers or leaders of start-up businesses with at least three years in operation, (b) employees of start-ups with assets of at least IDR 300 million, and (c) start-ups with a net worth of at least IDR 50 million per year and sales proceeds of at most IDR 300 million. The study's target sample comprised 300 owners or managers of start-up businesses in the two named provinces. This study used a semantic differential bipolar scale approach ranging from 7 (very strongly suitable) to 1 (very strongly unsuitable). The contingency approach was carried out by considering two typologies of each opposite variable, namely, competitive intensity/CI (benign vs hostile) and organisational learning culture/OCL (hierarchy vs adhocracy). For business strategy variables (imitation vs innovation) and remote transformational leadership, this study used a scale interval from 7 (very strongly pressured) to 1 (very strongly unpressured). For the service performance variable or SERVPERF, this study used a 7-point Likert scale with a score ranging from 7 (very high) to 1 (very low). Service performance as perceived by managers was compared with the competitor's service performance for the last five years using the self-report approach. This has also been done and is recommended by Muafi and Kusumawati (2020; Govindarajan, 1988). The study used the statistical technique of Euclidean distance (ED) regression. To analyse the moderating influence

Tab. 1. Variables, descriptions, indicators, and the measurement scale

No.	Variable	Operational definition	Indicator/sources	Measurement scale	
1.	Competitive Intensity (CI)	The level of competition faced by the company that has an impact on the company's strategic decision-making	Number of competitors Market growth rate Uncertainty of demand Product characteristics (Homburg et al., 2002; Syahbana, 2008; Porter, 1980; Hill, 2015)	Benign Score 1 (very strongly unsuitable) 1. Number of competitors is relatively small 2. The market growth rate can be controlled 3. Market demand is predictable 4. Lack of product/service differentiation offerings	Hostile Score 7 (very strongly suitable) 1. Many competitors 2. The market growth rate can be controlled; 3. Market demand cannot be easily predicted 4. Do not have a product/service differentiation offering
2.	Organisational Learning Culture (OLC)	Company skills in creating, acquiring, transferring knowledge, and modifying it to reflect new knowledge and insights	Organisational learning orientation The leader's orientation to organisational learning Promoting the value of organisational learning The effectiveness of organisational learning (Islam et al., 2015; 2016; Cameron & Quinn (2011; 1999; Quin & Cameron, 1988)	Hierarchy Score 1 (very strongly unsuitable) Have expertise in coordination, monitoring, and organising Behave efficiently in decision-making Have consistency in acting and behaving, and be on time every time there is a change Control and efficiency in new business processes/activities	Adhocracy Score 7 (very strongly suitable) Have expertise in innovation and always visionary Emphasise aspects of entrepreneurship in decision-making Agile transformation/ agile in every change Always oriented to effectiveness in new business processes/activities
3.	Business Strategy (BS)	Company strategy in serving products/ services to customers	Cost and time The principle of prudence Fundamental changes and updates of ideas and innovations Fundamental changes and updates in the product, process, administration, and service innovation (Sen & Ghandforoush, 2018; Wanasika & Conner, 2011; Lee & Zhou, 2012)	Imitation Unpressured	Innovation Pressured
4.	Remote transformational leadership (RTL)	Leaders' ability to transform organisational resources optimally to achieve meaningful goals by minimising the physical and face-to-face interaction with employees through information technology, either with a schedule or unplanned	Individualised influence Inspirational motivation Intellectual stimulation Individualised consideration (Kelley & Kelloway, 2012; Kelloway et al., 2013)	Scale 1 Unpressured	Scale 7 Pressured

5.	Service Performance	The performance produced by the company compared to the performance of the competitors during the last five years Indicator: ***Time,*** namely, the quality and quantity of service time provided and considered by the customer ***Accessibility,*** namely, the access or convenience for consumers to access the location of service providers ***Completeness,*** namely, the company's ability to provide facilities and infrastructures to customers ***Courtesy,*** namely, the contact attitude of employees to pay attention and understand customer needs, knowledge, friendliness, politeness, good communication, and ease of communication ***Responsiveness,*** namely, the ability or desire of employees to help and provide services needed by consumers, a sense of employee responsibility and the desire to provide excellent service, and help consumers when they face problems related to the service provided	Time Accessibility Completeness Courtesy Responsiveness (Cronin & Taylor, 1992; 1994)	Scale 1 Very low, below average competitors	Scale 7 Very high, above average competitors

of remote transformational leadership, the research used the Euclidean distance simple regression and Euclidean distance simple regression moderation. The results of testing the questionnaire items from each variable are valid and reliable. Variables, operational definitions, indicators, items, and the measurement scale are given in Table 1.

The contingency approach can be achieved by calculating the Euclidean distance (misfit of the business strategy score) by considering the competitive intensity and the organisational learning culture variable. To make the analysis easier, the following equations were used to test hypotheses 1–4:

$$Y = Bo + B1 \text{ Dist } X1X2 + e \quad (1)$$

$$Y = Bo + B1 \text{ Dist } X1X3 + e \quad (2)$$

Y = Service Performance (dependent variable)

Bo = constant

B1 = regression coefficient

Dist X1X2 = Euclidean distance business strategy and competitive intensity (X2)

Dist X1X3 = Euclidean distance business strategy and organisational learning culture (X3)

Furthermore, the following equation was used to test hypotheses 5–7:

$$Y = Bo + B1 \text{ Dist } X1X2.Z + e \quad (3)$$

$$Y = Bo + B1 \text{ Dist } X1X3.Z + e \quad (4)$$

Y = Service Performance

Bo = constant

B1 = regression coefficient

Dist X1X2.Z = Euclidean distance business strategy and competitive intensity (X2) with Z moderation (remote transformational leadership)

Dist X1X3.Z = Euclidean distance service innovation strategy and organisational structure (X3) with Z moderation (remote transformational leadership)

It needs to be known that The Euclidean distance score is the fit between variables; the smaller the score, the closer the relationship distance between variables. Therefore, this will have a negative influence on service performance and vice versa.

3. Research results

3.1. Respondents' characteristics

The majority of respondents for this study were male (77 %), with at least 5–10 years of experience (65 %) and a bachelor's degree (62 %) and tended to choose the innovation strategy (51 %).

3.2. Hypothesis testing

Based on the results of data grouping, two groups of strategies emerged: imitation (code 1 with n=113) and innovation (code 2 with n=118). The results of the hypothesis testing in Table 1 used the Euclidean distance simple regression and concluded that hypotheses 1 to 4 were accepted (sig. ≤ 0.05). This means a fit of the business strategy (imitation) with the benign competitive intensity and hierarchy OLC in improving service performance and vice versa.

Furthermore, in the hypothesis testing using Euclidean distance simple regression moderation, it was concluded that hypotheses 5 to 8 were accepted (sig. ≤ 0.05). This means that partially, remote transformational leadership was able to strengthen the fit of the business strategy with the benign competitive intensity and hierarchy OLC and vice versa.

4. Discussion of the results

Based on the statistical test results, all hypotheses were accepted. The owners and service managers of start-up businesses in DIY and East Java Province tend to implement the innovation strategy rather than the imitation strategy. This indicates that the innovation strategy is considered as more able to improve service performance to customers. The data analysis results concluded that the innovation strategy fits in the case of the hostile competitive intensity and the adhocracy OLC and vice versa so that service performance can be improved. These findings also support the previous research conducted by Estrada-Cruz et al. (2020; Tiantian et al., 2013; Al-Rfou, 2012; Hoque, 2011; Chen, 2010) and reject the findings from Teller et al. (2016; Assaf & Cvelbar, 2011; Fosu, 2013; O'Brien, 2003). Gronroos (1997) suggested that companies faced with hostile competitive situations should adopt a service-based business strategy to increase customer value and strengthen customer

Tab. 2. Summary of the regression test result

Regression equation model	N	R^2	Constant	Coefficient (beta)	t	Sig.
H1. Y = a + b1 dist Imit.CI+e	113	0.035	3.507	-0.188	-2.023	0.040*
H2. Y = a + b1 dist Imit.OLC+e	113	0.121	4.383	-0.348	-3.930	0.000*
H3. Y = a + b1 dist Imit.CIZ+e	113	0.038	22.875	-0.194	-2.097	0.038*
H4. Y = a + b1 dist Imit.OLCZ+e	113	0.114	26.766	-0.338	-3.798	0.000*
H5. Y = a + b1 dist Innov.CI+e	118	0.063	4.868	-0.251	-2.810	0,006*
H6. Y = a + b1 dist Innov.OLC+e	118	0.075	3.639	-0.274	-3.084	0.003*
H7. Y = a + b1 dist Innov.ICZ+e	118	0.076	9.283	-0.276	-3.102	0.002*
H8. Y = a + b1 dist Innov.OLCZ+e	118	0.039	19.050	-0.199	-2.192	0.030*

Note= *sign <0.005

relationships. Indonesia is known for its very intense start-up business competition. Two fintech sub-sectors seem to dominate, namely, lending and e-money. In terms of the number of players, fintech lending has far more players than e-money, but e-money is dominated by big players. It is predicted that e-money will become the most potential fintech sub-sector. Like money in a wallet, an e-money balance is designed to help users make transactions to fulfil their daily needs. Start-up business players mostly fear weak demand with very high fixed operating costs and the inability to innovate because of lagging behind their competitors. This results in price wars by reducing costs. The consequence is that the company inevitably implements the imitation strategy. This condition is exacerbated by the Covid-19 pandemic, which has a very high level of uncertainty.

The imitation strategy is still believed to provide benefits, such as low prices, easier market education, fewer product failures, low research and development budgets, low costs for employee training and development, and low costs for organisational learning for employees.

Companies can absorb existing knowledge to produce something new so that they can offer unique products and services. When implementing the adhocracy OLC, start-up businesses should be more oriented towards innovation and creativity. This certainly must also be supported by the use of a consistent strategy in the long term.

Therefore, this study supports the research findings by Khurosani (2013), who recommended that organisations should strengthen freedom value, learning commitment, and leaders' work creativity when they want to implement the adhocracy culture. This condition will also influence market responsiveness so that start-up businesses in DIY and East Java Province will increasingly have above-average performance compared to their competitors.

As stated by Agrawal (2020), company characteristics can make companies more confused in determining their work patterns. The era of the Covid-19 pandemic requires companies to be flexible in adapting to the situation and conditions of the uncertain business environment. The leadership must ensure the organisation continues to move dynamically and does not lag behind its competitors. In this case, remote transformational leadership is required for carrying out the company's mission and instilling a sense of pride in subordinates, communicating an attractive vision, modelling appropriate behaviour, encouraging to innovate in problem-solving, creatively developing self-efficacy, encouraging to set challenging goals or objectives and paying special attention to the needs of each employee to excel and develop. The concept of remote work has been widely applied by companies due to the Covid-19 pandemic. It has been used by owners and managers of start-up businesses in DIY and East Java Province either through scheduled or unplanned communication for required sudden instructions. This study also supports the findings by Kelloway et al. (2013) that remote transformational leadership can strengthen the emphasis on the importance of having an innovation strategy in situations of volatile competitive intensity and vice versa. It also supports the findings by Yang & Yang (2018) that the influence of the interaction between transformational leadership and competitive intensity can improve company performance; thus, employees would be more creative and able to strengthen high-performance work systems. This is also strengthened by the study carried out by Lilian (2020) that company leaders must have knowledge about the adoption of information technology and communication in the pandemic era so that it is easier to provide policy and strategic direction to be carried out by the company. The fundamental task of leaders is to motivate their followers to achieve great things and to continue significantly contributing to business growth and organisational success in the future.

Several strategies for start-up businesses need to be considered and can be implemented currently. First, an organisation should focus on its mission to serve the wider community. This is important since the breadth of the market served will attract capital investors. Second, companies are suggested to continuously interact with investors to keep them in the business in the future. The company must have sufficient capital for its operations from six months to one year. Third, the company must study the business model that will be applied, such as choosing a business model for direct services (on-demand), subscription, joining the marketplace, and even freemium. This is surely important since it will have an impact on the company's costs and benefits. Fourth, the company must innovate by creating new products or services utilising the existing resources and abilities to get new sources of income while focusing on customer satisfaction and delight. Fifth, there should be effective and efficient automation of business processes to save costs, quickly respond to situations by avoiding multi-layered online queues, evaluate errors, and reduce service complexity so that more referrals are loyal to the company. Sixth, the company must establish and strengthen networks with communities that have the potential to attract new investors and customers, retain old customers, or even collaborate with other start-up companies. Several other strategies can also be used while improving service performance in terms of time, accessibility, completeness, courtesy, and responsiveness.

The results of this study were also followed up by interviews with four start-up business service managers (R1–R4) in DIY and East Java Provinces.

"Innovation strategy is currently needed by launching our new and different products and services… This is necessary considering that nowadays people are getting used to using it, but indeed, it is for certain customer segments. It has not been aimed at all segments, let alone for people in rural areas who are still very unfamiliar to this." (R2)

"We are currently improving our service quality, especially in the era of the Covid-19 pandemic. Sometimes, every day we have to design innovatively; about how we create products and services that have short queues so that consumers don't get confused when making transactions. We do this as an effort so that we can survive amid the intense competition. We certainly do this by sticking to the protocols set by the government. That is why, I, as the leader, usually provide instructions or order via Zoom, WhatsApp, and even emails." (R3)

"Indeed, in using our strategy, we are very aggressive and expansive to target all segments. We usually also look at our competitors' products and services as we imitate and add some changes. We do this because we are usually constrained from the aspect of research and development costs. We also do not forget to pray so that the Covid-19 pandemic would be over soon." (R4)

"In order to win the competition, we need to be flexible. We need to be agile to seize opportunities. The era of the Covid-19 pandemic makes us also faced with difficult conditions. On the one hand, we have to serve our customers satisfactorily, yet on the other hand, we also have to calculate the cost and benefit. We must survive and stay ahead in this era and the future." (R4)

"For us, we have to be agile during the pandemic. We have to be flexible with the rules. This is important so that we do not run into a rigid bureaucracy. But we still adjust it to the strategy we choose." (R1)

A balanced number of owners and service managers of start-up businesses in DIY and East Java Province are choosing between and implementing innovation and imitation strategies. The dominant consideration is the cost of research and development, especially during the Covid-19 pandemic. The role of remote transformational leadership is especially helpful in strengthening leaders and employees in carrying out business models with agreed strategic agreements.

5. Implication

5.1. Managerial implication

Companies should have an agreement in implementing their business strategy. It is important to consider competitive intensity and the organisational learning culture faced by start-up businesses. The situations and conditions faced by companies are certainly very different. Pressure from stakeholders, especially if they dominate, could also influence strategic decision-making.

OLC must change or modify mental models of leaders and employees, processes, rules, behaviour, or knowledge as a dynamic process of creation, acquisition, and integration of useful knowledge to build resources and capabilities that contribute to the improvement of the company's service performance. Remote transformational leadership can be used by maintaining the company's environment so that it promotes the exchange of information and knowledge and supports its service performance.

5.2. Theoretical implication

The study's theoretical implications are related to the important contribution of competitive intensity and the organisational learning culture (OLC) to the contingency approach. Each contingency variable typology must be adjusted to the business strategy typology to increase service performance. The situation and conditions improve when strengthened by the role of remote transformational leadership.

5.3. Research limitations

This study has several limitations and research gaps.

- The study sample was only taken from two provinces, namely DIY and East Java. Therefore, the findings cannot be generalised for all owners and service managers of start-up businesses in Java Island or Indonesia.
- The primary data on the perceptions of the owners and service managers were collected during the Covid-19 pandemic. The answers might have been hasty and lacked focus. Therefore, the research was completed using data from interviews with several key service managers.
- Service performance was measured by comparing the company's own performance and competitors' performance over the last five years. Conditions during the Covid-19 pandemic were extremely difficult to observe.
- This study combined the research data from start-up businesses that have not been grouped into business types. In the future, it should be separated to provide strategic recommendations and policies that are appropriate and in line with the conditions and type of the company.
- There are other contingency variables that need to be considered, such as organisational structure, corporate strategic behaviour, green HR practices, and others. Such future studies would enrich theoretical and managerial contributions.

Conclusions

This study aimed to find the appropriate strategy for achieving excellent service performance for start-up businesses in an emerging market, namely, Indonesia. Specifically, the author has fit the company's business strategy with the condition of their competitive intensity and organisational learning culture. Also, the author considered the moderating role of remote transformational leadership in strengthening the relationship between competitive intensity, organisational learning culture, and business strategy in improving service performance.

The hypothesis test results and discussion of the findings revealed that all hypotheses were accepted. In this regard, the study confirmed that the fit between the business strategy, competitive intensity, and organisational learning culture enhances the company's service performance. The benign competitive intensity, hierarchy organisational learning culture and implemented imitation strategy improve service performance. The hostile competitive intensity, adhocracy organisational learning culture and innovation strategy improve the service performance. Finally, the findings also suggest that both relationships become stronger when the leader of the start-up business adopts the remote transformational leadership style.

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Integrated maintenance, inventory and quality engineering decisions for multi-product systems

Ali Salmasnia Rahil Hafezian
Mohammad Reza Maleki

ABSTRACT
It is essential for manufacturers to consider the interrelation among quality, inventory, and maintenance decisions to detect imperfect quality products, keep the production system in good operating condition, and manage quality and inventory costs. Hence, this paper aims to develop an integrated model of inventory planning, quality engineering, and maintenance scheduling in which the expected total cost per time unit is minimised by determining the sample size, sampling interval, control limit coefficient, along with production cycle time. In this regard, an imperfect multi-product manufacturing system is considered, in which the inventory shortage in satisfying the demand for each product type and the idle time during the production cycle are not allowed. It is assumed that the process starts in an in-control condition where most produced units are conforming. However, due to the occurrence of an assignable cause (AC), the process mean moves to an out-of-control condition in which a significant fraction of non-conforming units is produced. The efficiency of the proposed mathematical model is evaluated by a numerical example, and then the sensitivity of the proposed model to important inputs is analysed. Finally, a comparative study based on the Taguchi design approach is given to confirm the capability of the proposed model to achieve remarkable cost savings.

KEY WORDS
multi-product system, production planning, maintenance scheduling, control chart, inventory planning, imperfect production system

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Mohammad Reza Maleki

Industrial Engineering Group, Golpayegan College of Engineering, Isfahan University of Technology, Golpayegan, Iran.

ORCID 0000-0002-6005-3046

Corresponding author:
Email: M.maleki@iut.ac.ir

Ali Salmasnia

University of Qom, Iran
ORCID 0000-0001-9263-2520

Rahil Hafezian

University of Qom, Iran

Introduction

Increasingly more companies are moving towards producing several items by a single machine to increase production efficiency, stock different produced items and reduce the total cost over the planning horizon. Using a multi-product manufacturing system increases manufacturing productivity by satisfying customer orders faster and more economically. A multi-product production planning problem aims to reach the optimum order and configuration

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of products by minimising the expected total cost and requires an all-around look at different aspects of the problem. Since multi-product systems usually use expensive and complex equipment, it is imperative to keep them in a suitable operational condition by implementing efficient maintenance scheduling. Maintenance activities usually require the suspension of the manufacturing cycle which increases the total production cost. This issue is clearly in conflict with manufacturer cost objectives. However, overhauling the system components reduces the rate of non-conforming products, and consequently, the quality-related costs are decreased remarkably. As another important issue, it is essential to detect process anomalies quickly to satisfy customer expectations. By optimising the sample size, sampling interval, and control limit coefficient, quality control charts lead to decreasing production costs due to a reduction in non-conforming items. Classical economic production quantity (EPQ) models have some technical drawbacks as follows: (1) they fail to consider imperfect production, which may be caused by the fault of machines/equipment, labour mistakes, and deficiency of raw materials; (2) they fail to consider quality control decisions; and (3) they only consider single output whereas, in practice, several products are often produced by a unique set of machines to reduce the system's idle time. Because of mentioned drawbacks and the interrelation among production planning, maintenance scheduling, and quality engineering concepts, the related decisions must be made simultaneously.

Most studies in the context of statistical and economical process quality control, inventory planning, and maintenance scheduling have neglected their interrelation. However, only a few papers in the literature have integrated these concepts, particularly in multi-product systems. In the late 1950s, different researchers attempted to formulate production scheduling to minimise production costs. Rogers (1958) extended a computational basis for economic lot scheduling and established a set of general equations for different scheduling situations. Taking setup time and setup cost into account, Bomberger (1966) provided a dynamic programming model for manufacturing different products in a multi-product production system. By modifying the drawbacks of previous research efforts, Madigan (1968) proposed a simple method for solving scheduling issues of multi-product, single-machine companies. Stankard et al. (1969) suggested a heuristic algorithm to improve the dynamic programming provided by Bomberger (1966). After that, Hodgson (1970) extended a grouping procedure to obtain better results than Stankard et al. (1969), particularly in moderate and high-loading cases. Then, Backer (1970) presented some corrections to improve the method proposed by Madigan (1968) for solving deterministic multi-product inventory problems. Rosenblatt et al. (1986) explored the effect of an imperfect manufacturing system on the optimal production cycle length. They considered the condition in which the process deteriorates over time and produces a certain percentage of defective products.

The 1980s was the decade of quality discussions in industries, and researchers attempted to deal with the economic-statistical design (ESD) of control charts. In this context, Lorenzen and Vance (1986) introduced a general formulation for the economic design of control charts to obtain optimum values of sample size, sampling interval, and control limit coefficient. Amiri et al. (2014) developed a multi-objective ESD of the exponentially weighted moving average (EWMA) chart. They used two evolutionary algorithms, the non-dominated sorting genetic algorithm (NSGA-II) and the multi-objective genetic algorithm (MOGA), to obtain the optimum parameters of the EWMA monitoring scheme. Nenes et al. (2015) considered multiple assignable causes to probe the ESD of a variable-parameter (VP) Shewhart mean chart. Salmasnia et al. (2019a) established a multi-objective ESD model for the Hotelling T^2 monitoring strategy with double warning lines. They employed the NSGA-II algorithm to achieve proper nondominated solutions. Ershadi et al. (2021) suggested a tri-objective mathematical programming model for the ESD of simple linear profile charts. They combined the multiple objective particle swarm optimisation (MOPSO) algorithm with the response surface methodology (RSM) to optimise three objective functions of the total cost, in-control average run length (ARL_0), as well as out-of-control average run length (ARL_1). A multi-objective economic-statistical model for simple linear profile charts based on a hybrid NSGA-II/ RSM/TOPSIS framework was introduced by Roshanbin et al. (2022).

Regarding maintenance scheduling, Cho and Parlar (1991) reviewed the literature associated with the optimal maintenance and replacement models for multi-unit processes. Wang (2002) categorised different maintenance strategies for both single-unit and multi-unit processes and addressed the relationships among the existing models. To design optimal preventive maintenance (PM) and replacement strategies in repairable and maintainable systems, Moghadam et al. (2011) established a programming model to ascertain optimisation of the overall cost and system reliability during the planning horizon. Aiming at minimising the cost rate subject to a reliability constraint, Liu et al. (2019) focused on a maintenance planning problem for single-component systems. They provided a comparative study to evaluate and compare two age-based and reliability-based maintenance strategies using the degradation data of a real system. In contrast to Liu et al. (2019), Kamel et al. (2020) developed a maintenance scheduling approach for complex repairable systems. They optimised the maintenance cost, including random failure cost, repair cost, replacement cost, and total planned downtime cost, in a way that the system availability satisfies a pre-specified level. Under the uncertainty of product demands, a maintenance planning model for the flexible multistage processes in multi-specification and small-batch production was developed by Zhou et al. (2021). Hu et al. (2022) suggested a linear Programming-enhanced RollouT (LPRT) for online maintenance scheduling, which optimises total maintenance cost by satisfying the system's reliability.

The integrated quality-maintenance models have received increasing interest in the literature. In this context, Tagras (1988) employed a Markov model and established general economic programming by incorporating quality monitoring and maintenance scheduling. Under the assumption that the mean parameter deviates from its nominal value due to equipment failure, Cassady et al. (2000) proposed a hybrid quality-maintenance policy by combining the chart and the PM strategy. To achieve lower costs related to quality, maintenance, and inspection activities, Linderman et al. (2005) studied joint optimisation of quality control and adaptive maintenance scheduling. Zhou and Zhu (2008) presented an integrated quality-maintenance model and employed a grid-search methodology to obtain the optimum model values that minimise hourly costs. Gouiaa-Mtibaa et al. (2018) integrated maintenance and quality decision by considering the impact of the system degradation on product quality. Salmasnia et al. (2018a) incorporated the ESD of an adaptive non-central chi-square monitoring scheme for simultaneous monitoring of mean and variability parameters with maintenance scheduling. Salmasnia et al. (2020a) proposed a unified model research by combining the ESD of a VP monitoring scheme with condition-based maintenance for two-unit series processes. They utilised the particle swarm optimisation (PSO) method to optimise the expected total cost per time unit under some statistical constraints. Interested readers may refer to Chen et al. (2011), Mehrafrooz and Noorossana (2011), Liu et al. (2013), and Xiang (2013) for detailed information on joint investigation of quality and maintenance management.

In the recent decade, joint consideration of production planning and maintenance strategy has gained growing attention within both academia and industry. In this regard, taking safety stock and maintenance into account, Pal et al. (2014) proposed a hybrid multi-echelon production-inventory model consisting of a manufacturer, supplier, and retailer. To achieve the values of production planning and maintenance planning variables in multi-state systems, Saeidi-Mehrabad et al. (2017) combined production and PM schedule. Considering a multi-product system, Liu et al. (2015) introduced an integrated model by combining the EPQ model and PM strategy.

Concerning hybrid maintenance-inventory-quality models, Ben-Daya and Makhdoum (1998) narrowed their focus to probe the impact of different PM strategies on the combination of the EPQ model and the economic design of the control chart. Taking an imperfect production system into account, Pan et al. (2012) combined the concept of statistical process monitoring (SPM) and maintenance planning with the classical EPQ model. Nurelfath et al. (2016) designed an optimisation model to obtain the optimum values of production planning, maintenance strategy, and SPM-related variables. They found that increasing the PM level leads to a reduction in quality monitoring costs. Salmasnia et al. (2017) extended a hybrid model based on production run length, maintenance schedule, and SPM based on multiple assignable causes. A hybrid maintenance-production model under the VP-T2 monitoring scheme was proposed by Salmasnia et al. (2018b). Fakher et al. (2018) focused on a multi-period multi-product capacitated lot-sizing problem and analysed the trade-off among maintenance, quality, and production. By employing a non-uniform sampling strategy, Salmasnia et al. (2020b) recommended another unified model based on production planning, maintenance management, and ESD of the control chart by taking the time value of money and the stochastic shift magnitude into account. Salmasnia et al. (2019b) studied the ESD of an adaptive non-central chi-square control chart considering production planning and maintenance scheduling. Salmasnia et al. (2022) proposed a unified production-maintenance-quality

Tab. 1. Summarised literature review

Author(s)	Concept(s)			Number of products		Solution approach	Time to shift distribution
	SPM	Maintenance	EPQ	Single	Multiple		
Rogers (1958)			✓		✓	Manual incremental	-
Salmasnia et al. (2018b)	✓	✓	✓	✓		PSO	Exponential
Salmasnia et al. (2019a)	✓			✓		NSGA-II/DEA	Exponential
Salmasnia et al. (2019b)	✓	✓	✓	✓		PSO	Weibull
Bomberger (1966)			✓		✓	Dynamic programming	-
Salmasnia et al. (2020a)	✓	✓		✓		PSO	Exponential
Madgan (1968)			✓		✓	Innovative algorithm	-
Rosenblatt et al. (1986)			✓	✓		Analytical	Linear / exponential
Lorenzen and Vance (1986)			✓	✓		Numerical technique	-
Liu et al. (2015)		✓	✓		✓	Integer programming	Exponential
Nourelfath et al. (2016)	✓	✓	✓		✓	mixed integer programming	Weibull
Chen et al. (2011)	✓	✓	✓	✓		Loss function	Exponential
Salmasnia et al. (2017)	✓	✓	✓	✓		PSO	Weibull
Lee et al. (2012)	✓			✓		Genetic Algorithms	Exponential
Nenes et al. (2015)	✓			✓		Markov chain	Erlang
Yu et al. (2010)	✓			✓		-	Exponential
Chen and Yang (2002)	✓			✓		Optimization model	Weibull
Makis and Fung (1998)	✓		✓	✓		Optimization model	Weibull
Linderman et al. (2005)	✓	✓		✓		Design of Experiments (DOE)	Weibull
Zhou and Zhu (2007)	✓	✓		✓		Grid search approach	Weibull
Yin et al. (2015)	✓	✓		✓		-	Weibull
Le Tang (2012)	✓	✓		✓		-	Exponential
Xiang (2013)	✓	✓		✓		Markov processes	Exponential
Mehrafrooz and Noorossana (2011)	✓	✓		✓		-	Exponential
Kuo (2006)	✓	✓		✓		Markov decision process	Binomial
Pan et al. (2012)	✓	✓	✓	✓		Hessian matrix.	Weibull
Rahim and Ben-Daya (1998)	✓		✓	✓		Non-Markovian Model	Weibull
Ben-Daya and Makhdoum (1998)	✓	✓	✓	✓		x-bar	Weibull
Salmasnia et al. (2020b)	✓	✓	✓	✓		PSO	Weibull
Beheshti Fakher et al. (2018)	✓	✓	✓		✓	Linear mixed-integer programs	Weibull
Gouiaa-Mtibaa et al. (2017)		✓	✓	✓		Lemma	-
Saidi-Mehrabad et al. (2017)		✓	✓		✓	CPLEX	Exponential
Salmasnia et al. (2022)	✓	✓	✓	✓		PSO	Weibull
This paper	✓	✓	✓		✓	PSO	Exponential

model when multiple assignable causes may affect mean and/or variance parameters. Table 1 represents an overview of the literature review considering important features of related previous studies.

Considering a multi-product system, the present article study presents a hybrid mathematical formulation to optimise the expected total production cost unit (ETCU) during each cycle. The proposed model involves the inventory cost, including holding and ordering costs, corrective and preventive maintenance costs, as well as sampling and quality control costs. Moreover, the optimal values of chart parameters, including the sample size, sampling interval between two consecutive subgroups, control limit coefficient, and cycle time, are obtained through the minimisation of ETCU. To do so, it is assumed that the system starts with an in-control situation and shifts to an out-of-control state when an assignable cause occurs.

The structure of this paper is organised as follows: the next section is devoted to theories, notations, and methodical aspects used for problem definition. The suggested mathematical formulation that combines production planning, maintenance scheduling, and quality control decisions is presented in Section 2. A solution approach for solving the proposed mathematical programming model is presented in Section 3. A numerical example, along with comparative study, is given in Section 4. In addition, the model behaviour is investigated through a sensitivity analysis across the important parameters of the proposed mathematical formulation in this section. Finally, the last Section is dedicated to the concluding remarks and recommendations for future studies.

1. Problem definition

To improve the accuracy of existing models, this study attempts to integrate inventory management, control chart, and repair-maintenance scheduling in a multi-product production process. The demand pattern for each produced item is assumed to be constant, and the developed programming model attempts to minimise the total manufacturing cost through optimisation of production cycle time and other decision variables. It is supposed that the production process starts with an in-control situation and may move to an out-of-control one when an unobservable assignable cause occurs. The occurrence of the assignable cause can be the consequence of the process nature, machine deterioration, change in machine setting, a bad batch of raw material, and operator errors which lead to a higher rate of non-conforming products.

The $\bar{X}$ Shewhart chart is used to trace the disturbances of the study quality characteristic. This chart issues an out-of-control signal when an assignable cause affects the process mean level. The study quality characteristic is a normally distributed variable with the in-control mean and standard deviation of μ_0 and σ_0, respectively. Due to the occurrence of assignable causes, the process mean deviates from its target value to $\mu_0 + \delta_u\sigma_0$ where δ_u denotes the shift magnitude. Note that the occurrence of the assignable cause significantly increases the rate of produced non-conforming items. In this case, if the $\bar{X}$chart detects the process deviation, then corrective maintenance (CM) activities are undertaken to restore the process to as-good-as-new condition. Otherwise, preventive maintenance (PM) operations are performed during set-up time to return the process mean to normal condition. Fig. 1 illustrates a different situation during each production cycle and maintenance policy for the system's renovation.

To formulate the objective function, the costs of each condition shall be calculated properly. The cost types during the production process are categorised into one of the following classes: 1) sampling costs, including variable and fixed costs; 2) quality costs for both in-control and out-of-control situations; 3) the inventory cost, including holding costs and other costs associated with storing produced items in a warehouse; 4) maintenance costs imposed by CM and PM activities; 5) false alarm costs; and 6) the set-up cost.

A manufacturing process that produces multiple items is investigated, where a production cycle is a complete run of all produced units. Since the production of a given item more than once during a production cycle may lead to shortage or system idleness, the focus is restricted to cases where each item is produced exactly once within a production cycle. In addition, the production and consumption time intervals for each product can be different. However, the sum of these two time intervals during a production cycle are equal for all products. Consider a company that produces three different products, each of which is produced once within each cycle. Let t_{p_i} denotes the production time of the i^{th} produced item. Fig. 2. depicts the ideal condition in which all items are produced exactly once, and the production cycle ends without shortage or idle time. In contrast to the ideal scenario, the shortage (Fig. 3) or system idleness (Fig. 4) occurs.

Remember that the decision variables in this article are the production cycle time (T) which is equal to the sum of t_{p_i}, the sample size (n), the sampling interval between two consecutive subgroups (h), and the control limit coefficient (l).

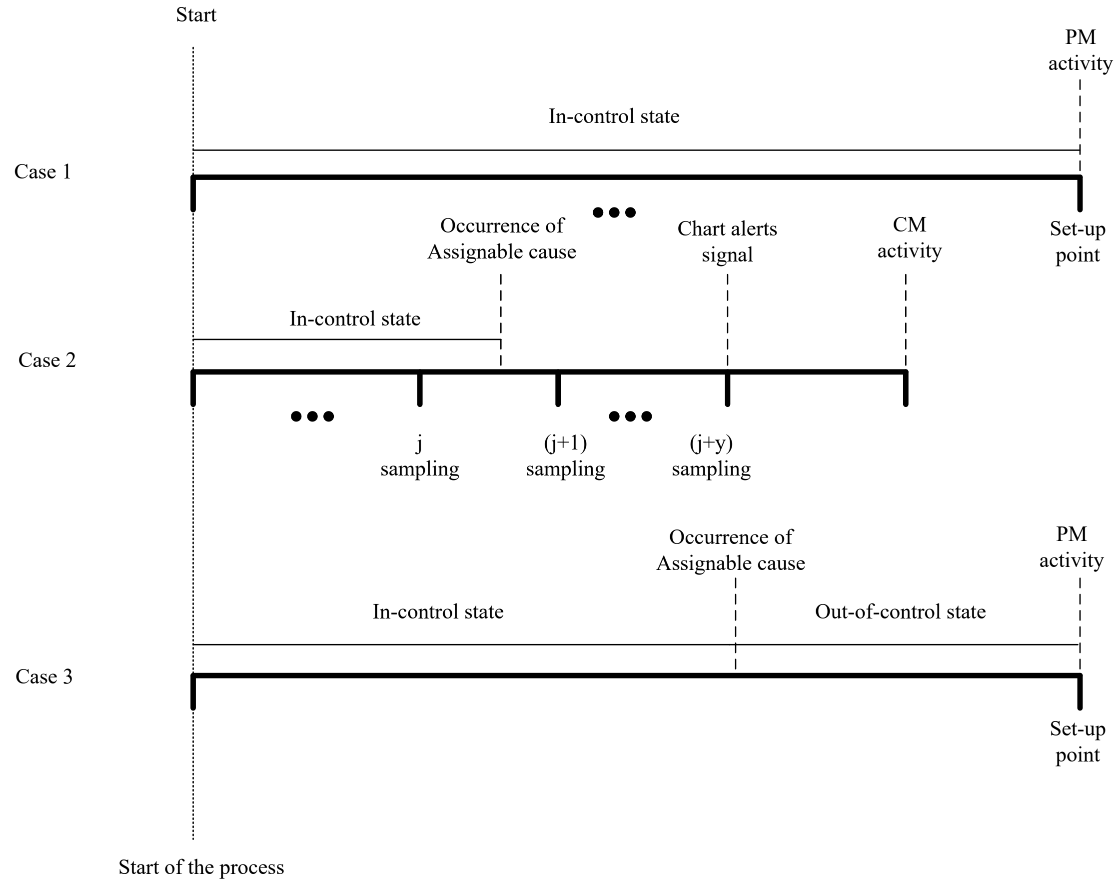

Fig. 1. Different scenarios in an operational cycle

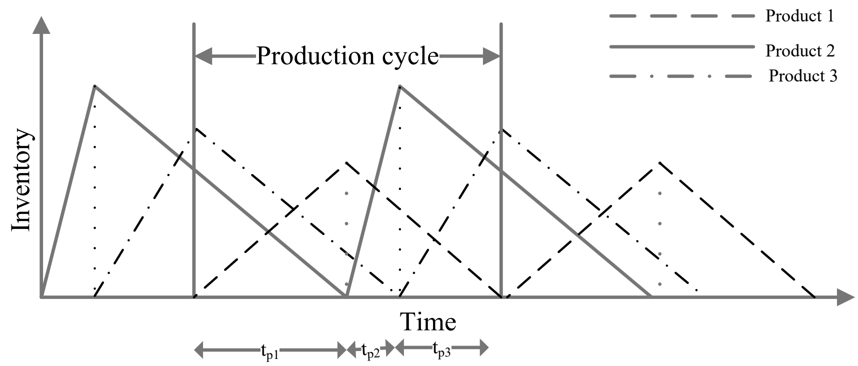

Fig. 2. Ideal condition, which is limited by $t_{p_i} = t_{p_j}$

1.1. Notations

This subsection defines all parameters used to formulate the proposed mathematical model. As illustrated in Table 2, the notations are classified into three general categories of indices, parameters, and decision variables.

1.2. Model assumptions

The assumptions in formulating the proposed mathematical programming model are outlined as follows:

1) The PM activity is performed before set-up time.

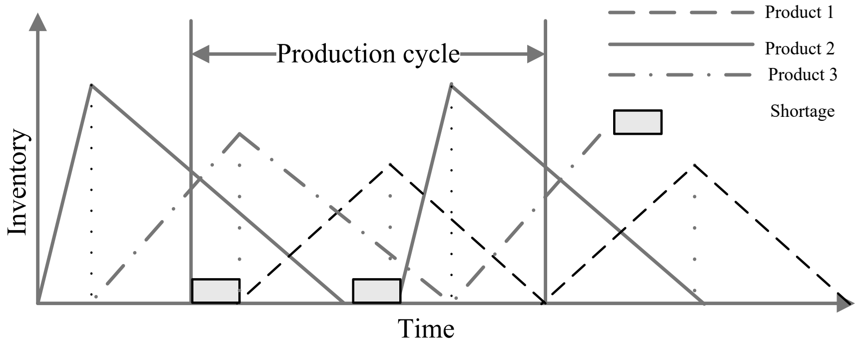

Fig. 3. Shortage case within the production cycle when $\boldsymbol{t_{p_i}} < \boldsymbol{t_{p_j}}$

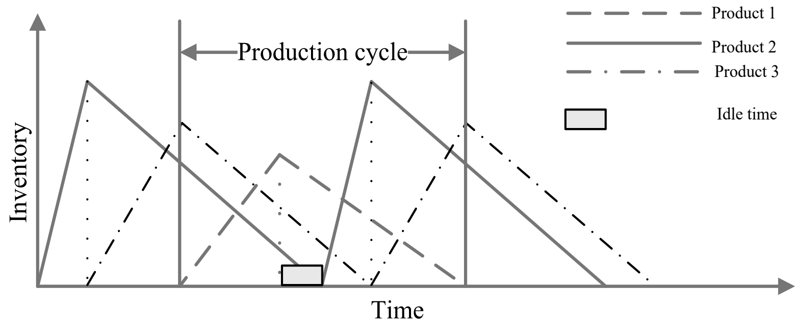

Fig. 4. System idleness within the production cycle when $\boldsymbol{t_{p_i}} > \boldsymbol{t_{p_j}}$

2) Time interval between the occurrence of two consecutive assignable causes follows an exponential distribution.

3) A production cycle is a complete run of all produced items, and each item is produced exactly once within a production cycle.

4) To avoid inventory shortage and system idleness within a production cycle, the sum of production and consumption time periods for all products are equal to each other. That is to say:

$$t_{p_i} + t_{d_i} = T_i = T \tag{1}$$

$$\sum_{i=1}^{k} t_{p_i} = T \tag{2}$$

5) To avoid inventory shortage and system idleness within a production cycle, we have $T_i = T$.

6) To avoid inventory shortage within each cycle, the following constraint is established:

$$p_i t_{p_i} = d_i \sum_{i=1}^{k} t_{p_j}, \forall i \tag{3}$$

7) The required times for implementing PM and CM activities, detecting ACs, and conducting system set-up are negligible.

8) CM activities start immediately after the detection of the assignable cause to restore the process mean to its in-control condition. This condition continues up to the end of the production cycle.

9) The process cannot return to its in-control condition when the assignable cause occurs.

10) Only one assignable cause exists during the production cycle.

11) The production process starts with an in-control state and moves to an out-of-control state when the occurrence ensues.

12) The process shifts are occurred independently according to homogeneous Poisson distribution.

13) The quality characteristic of interest is supposed to be a normally distributed variable. The occurrence of the assignable cause changes the process mean from its target value μ_0 to $\mu_0 \mp \delta_u \sigma_0$. Only increasing shifts are considered in this study because the probability of detecting increasing and decreasing mean shifts is the same.

14) The variance of the quality characteristic is not changed when the assignable cause occurs and remains unchanged during the production cycle.

2. Model description

In this section, the proposed mathematical model based on the integration of production planning, quality control, and maintenance schedule for a multi-product system is described. As previously mentioned, we assume that the process is in-control at the beginning of the cycle and may deviate from its in-control mean value during the production process when the assignable cause occurs. It is further supposed that the study quality characteristic, X, follows the normal distribution as $N(\mu_0, \sigma_0)$, where μ_0 and σ_0 are the target mean and standard deviation parameters, respectively. When a shift takes place, the mean level of the process changes from μ_0 to $\mu_0 + \delta_\mu \sigma_0$, and the model tries to use this variation for detecting the shift via a control chart and the process move to the out-of-control state. In such situations, it is crucial that the $\bar{X}$ chart detects the process disturbances as soon as possible. The total expected cost involves five cost elements, including the quality cost, sampling cost, inventory holding cost (IHC), maintenance cost, as well as set-up one.

2.1. Quality costs

The quality costs are incurred to ensure the conformance of produced items with the quality specification and/or to compensate for non-conforming outputs to achieve desired technical requirements. When the process mean level moves to an out-of-control condition, the percentage of nonconforming items extremely increases, and consequently, more quality costs are imposed on the manufacturer. For i^{th} product, when the mean parameter is out-of-control (in-control), the expected number of produced items is multiplied by the quality cost per unit under the out-of-control (in-control) condition. Thus, the expected quality cost per production cycle is given as:

$$E(QC) = \sum_{i=1}^{k} Q_{in_i} \times p_i \times ET_{in_i} + \sum_{i=1}^{k} Q_{out_i} \times p_i \times ET_{out_i} \quad (4)$$

where ET_{out_i} and ET_{in} denote the expected time which process stays in-control and out-of-control per production cycle. The value of ET_{out_i} is achieved by the following formula:

$$ET_{out_i} = TTD_i \times E(AC_i) \quad (5)$$

where $E(AC_i)$ is the expected occurrence number of assignable causes during producing i^{th} product per cycle while TTD_i is the time to assignable cause detection by the control chart. These values are given by Equations (6) and (7), respectively.

$$E(AC_i) = \int_0^{t_{p_i}} r(t)\,dt = t_{p_i}\lambda \quad (6)$$

$$TTD_i = h \times \min(ARL_{out}, N_i) - \tau \quad (7)$$

where $r(t) = \dfrac{f(t)}{1-F(t)}$ represents the defect rate whereas, N_i is the number of taken samples for i^{th} product during a production cycle, and τ denotes the expected in-control time within the sampling interval in which the AC takes place.

$$N_i = \left\lceil \frac{t_{p_i}}{h} \right\rceil \quad (8)$$

$$\tau = \frac{\int_{ih}^{(i+1)h} (t-ih) f(t)\,dt}{\int_{ih}^{(i+1)h} f(t)\,dt} = \frac{\left[1-(1+\lambda h)e^{-\lambda h}\right]}{\left[\lambda\left(1-e^{-\lambda h}\right)\right]} \quad (9)$$

Considering all products in a production cycle:

$$ET_{out} = \sum_{i=1}^{k} ET_{out_i} \quad (10)$$

$$ET_{in} = \sum_{i=1}^{k} ET_{in_i} \quad (11)$$

where:

$$ET_{in_i} = t_{p_i} - ET_{out_i} \quad (12)$$

2.2. Sampling cost

The expected sampling cost per production cycle, $E(S)$, consist of two variable and fixed elements. To obtain this cost element, the cost of taking each sample $(C_v \times n + C_f)$ must be multiplied by the total number of subgroups taken within a production cycle $\left(\sum_{i=1}^{k} N_i\right)$ as:

$$E(S) = \left(\sum_{i=1}^{k} N_i\right) \times (C_v \times n + C_f) \quad (13)$$

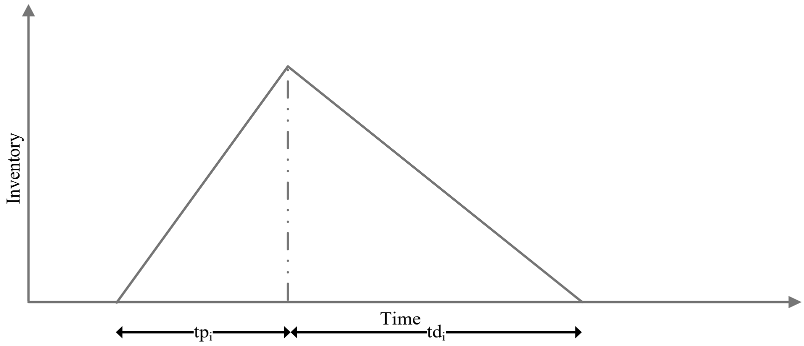

Fig. 5. Inventory approximation for product *i*

2.3. Inventory holding cost

As seen in Fig. 5, the inventory level for the i^{th} product increases during the production period and decreases since the consumption period begins. The inventory holding cost per production cycle (IHC) for i^{th} product can be derived by multiplication of inventory holding cost per time unit (H_i), production duration (t_{p_i}), the difference between production and demand rates ($p_i - d_i$), and the total duration of the production cycle (T). For all products, the IHC is calculated as follows:

$$E(H)=\sum_{i=1}^{k}\frac{(p_i-d_i)t_{p_i}T}{2}\times H_i \tag{14}$$

2.4. Maintenance cost

The total maintenance cost involves the costs incurred by the implementation of PM and CM activities, along with the cost of the false alarm. As mentioned, the CM tasks are implemented whenever the $\overline{X}$ chart detects the assignable cause (Fig. 6). Otherwise, according to Fig. 7, the PM tasks are undertaken at the beginning of the production cycle if the shift is not recognized by the $\overline{X}$ chart. The expected CM and PM costs per production cycle are obtained according to Equations (15) and (16), respectively.

$$E(CM)=\left(\sum_{i=1}^{k}E(AC_i)\right)\times C_{cm}\times(1-\beta) \tag{15}$$

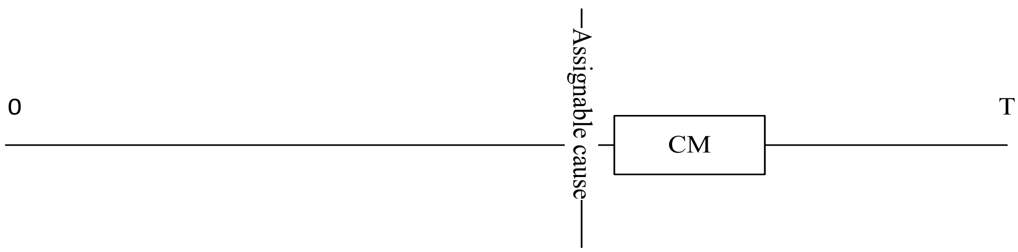

Fig. 6. Time of implementing CM tasks within the production cycle

Fig. 7. Time of implementing PM tasks

$$E(PM) = k \times C_{pm} \qquad (16)$$

The expected false alarm cost per production cycle ($E(f_a)$) can be obtained by multiplication of three elements of the expected number of subgroups under the in-control situation $\left(ET_{in}/h\right)$, probability of Type I error (α), the cost of each false alarm (C_{fd}):

$$E(fa) = \frac{ET_{in}}{h} \times \alpha \times C_{fa} \qquad (17)$$

The expected maintenance cost will be computed as:

$$E(M) = E(CM) + E(PM) + E(fa) \qquad (18)$$

2.5. Set-up cost

The set-up cost within each production cycle is the total cost required to prepare all products and is calculated as:

$$E(SC) = \sum_{i=1}^{k} S_i \qquad (19)$$

2.6. Cost function and constraints

Using the results of the previous subsections, the objective function and the constraints is written as:

$$\text{Min } ETCU = \left[E(S) + E(Q) + E(H) + E(M) + E(SC)\right]/T \qquad (20)$$

$$\text{S.t: } p_i t_{p_i} = d_i \sum_{j=1}^{k} t_{p_j}, \forall i \qquad (20.1)$$

where shows the total expected cost per time unit within a production cycle while constraint (20.1) prevents inventory shortages during cycle time. See Fig. 8 for more clarification regarding the significant features of the proposed multi-product mathematical model in comparison with the classical models.

3. Solution approach

Because of some complexities, the proposed mathematical model cannot be solved by analytical

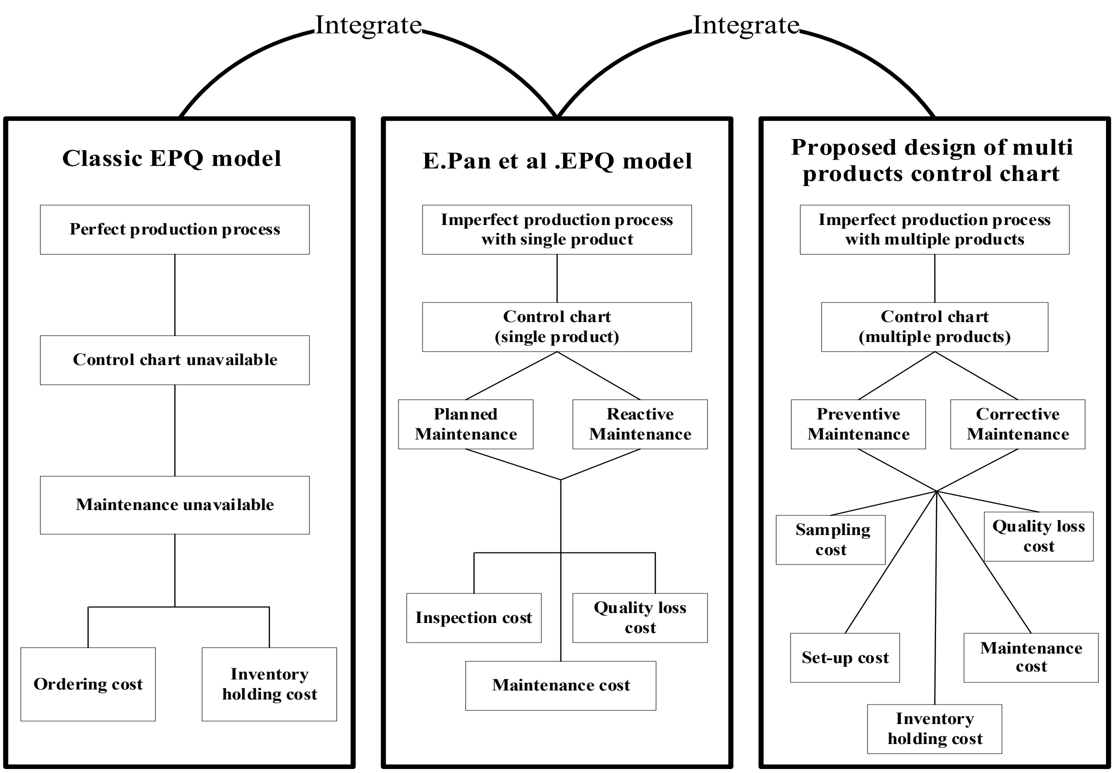

Fig. 8. Main features of the proposed mathematical model

methods. Some major complications are as follows: (1) the feasible area is non-convex and discontinuous; (2) some decision variables in the objective function are in the extreme bound of the integral or in the cumulative density function (CDF) of a (standard) normal distribution; and (3) the model includes both discrete and continuous decision variables.

Meta-heuristic algorithms are one of the up-to-date techniques for solving complex problems which have been extensively used to obtain desired results. Particle Swarm Optimisation (PSO) method is categorised as a meta-heuristic solution technique used to solve the developed numerical model efficiently as it can help in solving non-linear problems. Besides, it is a pioneer searching technique, which is easy to implement and has a simple concept.

3.1. PSO evolutional technique

The PSO, as a meta-heuristic searching algorithm, has been inspired by the social behaviour of a flock of birds looking for food or a bunch of fish.

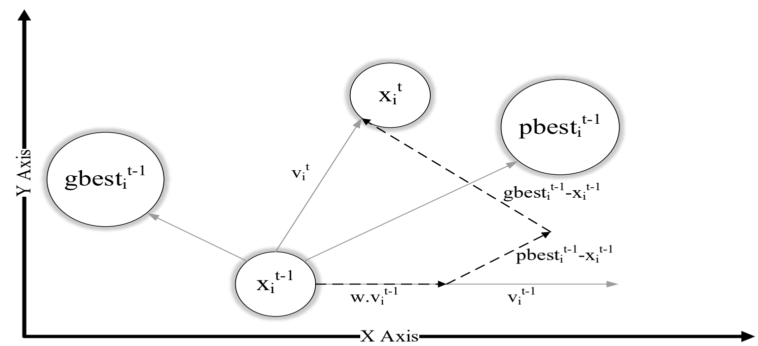

Fig. 9. Searching procedure in the PSO technique

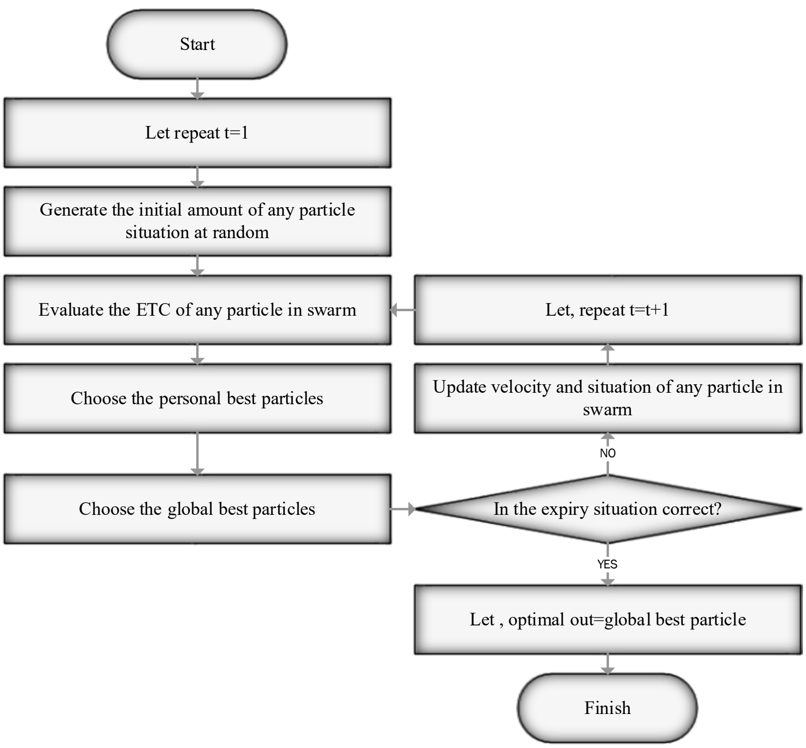

Fig. 10. Computational procedure of the PSO technique

Researchers found that this algorithm has a good performance for finding the optimal value of the decision variable in an optimisation problem. The method produces a random number of particles, and each particle, as one of the members of the population, tries to find the best position based on learning from itself and also from the other members of the group to improve the positions of particles in the solution path and finally finding the target, which is the best position and leads to the optimum value of the objective function. In this algorithm, particles sweep the problem space in accordance with the optimum experienced path of particles. Each particle has a velocity vector that determines the direction of the particle and also the objective function, which calculates the target value based on the particle's position and velocity.

This algorithm uses global and local searches to achieve high efficiency and is initialised with a random situation of particles that have velocities. Then, the algorithm searches to find the optimal value of the objective function by recalculating particle positions based on the two "best" values and the force of inertia. The first one is the best value, which itself was experienced in the solution path, which is named the personal best ( ), and the second is the best solution observed in the population, which is named the global best ( ). In each iteration, the particle will update its position and velocity after the calculation of the objective function and the related decision variable. The computational procedure of the PSO algorithm is summarised in Fig. 10, and a display of a searching point by the PSO algorithm in a feasible two-dimensional space is depicted in Fig. 9.

3.2. PSO implementation

Four-dimensional particles are considered, each of which is assigned to a certain decision variable, including the production cycle time (T), the sample size (n), the control limit coefficient (l), and the sampling interval between two consecutive samples (h). For producing the initial value of any continuous decision variable, as illustrated in the previous section, a uniform allocation of the random value is generated with regard to the allowable range of the decision variable. The amounts of discrete variables, i.e., the sample size (n), are achieved according to Eq. (21), respectively.

$$n = \min\left[\left(n_{\min} + floor\left(\left(n_{\max} - n_{\min} + 1\right) \times R\right)\right), n_{\max}\right] \quad (21)$$

where, n_{max} and n_{min} are the upper and lower range of n, respectively. Furthermore, R_1 is a uniformly distributed random number within the range (0,1).

4. Experimental results

This section investigates the efficiency of the proposed model to minimise the value of the expected total cost per time unit per production cycle subjected to model constraints. The proposed mathematical model is coded in MATLAB programming software, and its different aspects from both application and theory viewpoints are discussed based on the obtained results. Subsection 5.1 presents an industrial example in which the values of the cost objective function and problem decision variables are optimised through the PSO algorithm. In 5.2, using the Taguchi experimental design, the efficiency of the proposed hybrid model is compared with an alternative mathematical model, in which the quality, maintenance, and inventory decisions are made separately. Finally, in Subsection 5.3, a sensitivity analysis is performed on four parameters of: 1) the production rate of the i^{th} product during a production cycle, 2) the rate of quality cost under the out-of-control situation; 3) PM cost; and 4) cost incurred by each false alarm.

4.1. Numerical example

In this subsection, an industrial example presented by Salmasnia et al. (2017) and Pan et al. (2012) is employed to investigate the ability of the suggested formulation. In this example, a firm sells a certain food product to a wholesaler in packages of specified weights. According to Bisgaard et al. (1984), the weight of packages is selected as the quality characteristic of interest, and assignable causes can change the mean value of package weights. For one of the customers, the production and demand rates for three products are (60,30,20) and (40,20,8), respectively. The quality costs for each conforming and non-conforming product are (160,100,200) and (300,250,400). Each particular product has its own set-up time. To monitor the quality characteristic of interest, planned inspections are carried out periodically. At each inspection point, the fixed sampling cost per subgroup is considered as 25, while the variable sampling cost per item is equal to 4 units. Based on historical data, the occurrence of an assignable cause affects the process outcome and

Tab. 3. Parameter values

Parameter	d_i	p_i	k	Q_{in_i}	Q_{out_i}	S_i	λ
Value	(40،20،8)	(60،30،20)	3	(160،100،200)	(300،250،400)	(180،110،150)	0.02
Parameter	δ	H_i	C_f	C_v	C_{pm}	C_{cm}	C_{fa}
Value	1	(30،25،50)	25	4	2000	1000	100

shifts the mean parameter to $\mu_0 + \sigma_0$. The costs of implementing PM and CM tasks are 2000 and 1000 units, respectively. The cost incurred for each false alarm is 100 units. Finally, the set-up and holding costs are (180,110,150) and (30,25,50) per time unit. The values of the parameters are reported in Table 3.

The optimal values of decision variables obtained by the PSO algorithm are $[h^*, n^*, l^*, T^*] = [0.8831, 9, 1.7956, 3.9742]$, which leads to $ETCU^* = 13454.8552$. These values mean that the first sample with size $n = 9$ is taken after $h = 0.8831$ hour from the beginning of the production cycle. Moreover, the optimum length of the production cycle is calculated as $T = 3.9742$, implying that the PM tasks are conducted at the end of the cycle even though the process stays in-control. In addition, the control limit coefficient shall be considered at 1.7956.

4.2. Comparative study

In this subsection, the effectiveness of the developed hybrid inventory-quality-maintenance model referred to as "Model A", is compared with an alternative, in which the inventory, quality, and maintenance decisions are made separately ("Model B"). To make comparison studies more reliable and the results more defensible, these two models are compared under different scenarios. For this purpose, the Taguchi design is used to generate 27 scenarios under different values of the model parameters. The generated scenarios are presented in Table 4. Note that the values of other parameters are selected from Table 3. The obtained values of the expected total cost per time unit, along with the percentage of cost-saving for models A and B, are reported in Table 5. As expected, for all scenarios, optimising inventory-quality-maintenance decisions significantly increases the total cost imposed on the company. More specifically, an average reduction of about 20 per cent is achieved when the integrated model is replaced by the separated one. Table 6 contains each cost term obtained by Models A and B and their corresponding differences. It can be concluded from Table 6 that the impact of the set-up cost to reduce the cost function is more significant than others. Followed by the set-up cost, maintenance and quality costs have the greatest effect on the reduction of the total cost. On the other hand, since employing Model A leads to larger values of t_{p_i}, the sampling and holding costs obtained by Model A are both greater than those of Model B.

4.3. Sensitivity Analysis

In this subsection, a sensitivity analysis is presented to examine how the variation of four important parameters, including p_i (production rate during the production cycle), Q_{out_i} (quality cost under the out-of-control condition), C_{pm} (PM cost), and C_{fa} (false alarm cost), affects the optimum values of *ETCU* as well as model decision variables. To accomplish this, three different values are considered for each input parameter while other model parameters remain constant. The resulting values are given in Table 7 and in Figs. 11 to 14. The following conclusions are evident from the obtained results reported in Table 7.

1) According to Equations (4) and (14), p_i directly affects both inventory and quality cost formulas and consequently, $ETCU^*$ is considerably affected by the variation of the production rate (Fig. 11). For instance, when $[p_1, p_2, p_3]$ varies from [45 22 10] to [70 60 50], the optimal value of $ETCU^*$increases 1945 units. Moreover, it can be seen from Fig. 11 that by increasing $[p_1, p_2, p_3]$ from [45 22 10] to [70 60 50], the optimal values of h and T reduce. Moreover, as $[p_1, p_2, p_3]$increases from [45 22 10] to [60 30 20], the optimum value of n increases while further increment of $[p_1, p_2, p_3]$to [70 60 50] reduces the optimum value of the sample size from 9 to 6. The results confirm that there is no significant change in the optimum values of the control limit coefficient $l$when $[p_1, p_2, p_3]$ increases from [45 22 10] to [70 60 50].

2) As expected, as the value of quality cost under the out-of-control situation Q_{out_i}increases, the

Tab. 4. Generated scenarios through the Taguchi design (27 instances)

Instance	d_i	p_i	Q_{in_i}	Q_{out_i}	S_i	λ	δ	H_i	C_f	C_v	C_{pm}	C_{cm}	C_{fa}
1	[10 32 40]	[45 75 95]	[160 180 130]	[300 250 400]	[180 185 190]	0.1	1	[18 8 28]	15	4	3000	500	90
2	[30 10 40]	[50 80 100]	[180 200 150]	[500 460 600]	[200 205 210]	0.15	0.9	[20 10 30]	20	4	3000	500	90
3	[20 20 50]	[70 100 120]	[200 220 170]	[700 610 560]	[220 225 230]	0.2	1.1	[22 12 32]	25	4	3000	500	90
4	[20 20 50]	[70 100 120]	[200 220 170]	[500 460 600]	[200 205 210]	0.15	1	[18 8 28]	15	5	2400	800	90
5	[10 32 40]	[45 75 95]	[160 180 130]	[700 610 560]	[220 225 230]	0.2	0.9	[20 10 30]	20	5	2400	800	90
6	[30 10 40]	[50 80 100]	[180 200 150]	[300 250 400]	[180 185 190]	0.1	1.1	[22 12 32]	25	5	2400	800	90
7	[30 10 40]	[50 80 100]	[180 200 150]	[700 610 560]	[220 225 230]	0.2	1	[18 8 28]	15	6	4300	1000	90
8	[20 20 50]	[70 100 120]	[200 220 170]	[300 250 400]	[180 185 190]	0.1	0.9	[20 10 30]	20	6	4300	1000	90
9	[10 32 40]	[45 75 95]	[160 180 130]	[500 460 600]	[200 205 210]	0.15	1.1	[22 12 32]	25	6	4300	1000	90
10	[20 20 50]	[50 80 100]	[160 180 130]	[700 610 560]	[200 205 210]	0.1	1.1	[20 10 30]	15	6	2400	500	200
11	[10 32 40]	[70 100 120]	[180 200 150]	[300 250 400]	[220 225 230]	0.15	1	[22 12 32]	20	6	2400	500	200
12	[30 10 40]	[45 75 95]	[200 220 170]	[500 460 600]	[180 185 190]	0.2	0.9	[18 8 28]	25	6	2400	500	200
13	[30 10 40]	[45 75 95]	[200 220 170]	[300 250 400]	[220 225 230]	0.15	1.1	[20 10 30]	15	4	4300	800	200
14	[20 20 50]	[50 80 100]	[160 180 130]	[500 460 600]	[180 185 190]	0.2	1	[22 12 32]	20	4	4300	800	200
15	[10 32 40]	[70 100 120]	[180 200 150]	[700 610 560]	[200 205 210]	0.1	0.9	[18 8 28]	25	4	4300	800	200
16	[10 32 40]	[70 100 120]	[180 200 150]	[500 460 600]	[180 185 190]	0.2	1.1	[20 10 30]	15	5	3000	1000	200
17	[30 10 40]	[45 75 95]	[200 220 170]	[700 610 560]	[200 205 210]	0.1	1	[22 12 32]	20	5	3000	1000	200
18	[20 20 50]	[50 80 100]	[160 180 130]	[300 250 400]	[220 225 230]	0.15	1	[18 8 28]	25	5	3000	1000	200
19	[30 10 40]	[70 100 120]	[160 180 130]	[500 460 600]	[220 225 230]	0.1	1	[22 12 32]	15	5	4300	500	450
20	[20 20 50]	[45 75 95]	[180 200 150]	[700 610 560]	[180 185 190]	0.15	1.1	[18 8 28]	20	5	4300	500	450
21	[10 32 40]	[50 80 100]	[200 220 170]	[300 250 400]	[200 205 210]	0.2	1	[20 10 30]	25	5	4300	500	450
22	[10 32 40]	[50 80 100]	[200 220 170]	[700 610 560]	[180 185 190]	0.15	1	[22 12 32]	15	6	3000	800	450
23	[30 10 40]	[70 100 120]	[160 180 130]	[300 250 400]	[200 205 210]	0.2	1.1	[18 8 28]	20	6	3000	800	450
24	[20 20 50]	[45 75 95]	[180 200 150]	[500 460 600]	[220 225 230]	0.1	1	[20 10 30]	25	6	3000	800	450
25	[20 20 50]	[45 75 95]	[180 200 150]	[300 250 400]	[200 205 210]	0.2	1	[22 12 32]	15	4	2400	1000	450
26	[10 32 40]	[50 80 100]	[200 220 170]	[500 460 600]	[220 225 230]	0.1	1.1	[18 8 28]	20	4	2400	1000	450
27	[30 10 40]	[70 100 120]	[160 180 130]	[700 610 560]	[180 185 190]	0.15	1	[20 10 30]	25	4	2400	1000	450

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Tab. 5. Comparison of *ETCU* between Models A and B

INSTANCE	1	2	3	4	5	6	7	8	9
***ETCU* of model A**	17324.82	18866.51	22483.00	22046.67	17926.67	18157.07	19861.57	23113.83	19162.45
***ETCU* of model B**	22023.36	23567.65	27682.53	25494.30	20751.09	22086.29	26353.02	32340.28	26727.00
Cost savings(%)	21.33	19.95	18.78	13.52	13.61	17.79	24.63	28.53	28.30
Instance	10	11	12	13	14	15	16	17	18
***ETCU* of model A**	18458.67	19184.76	20145.33	20845.83	20423.02	20375.45	19960.03	20510.72	18688.63
***ETCU* of model B**	21540.41	22808.86	23537.83	27541.16	28628.56	27429.08	24960.78	25136.27	22723.04
Cost savings(%)	14.31	15.89	14.41	24.31	28.66	25.72	20.03	18.40	17.75
Instance	19	20	21	22	23	24	25	26	27
***ETCU* of model A**	18596.84	21495.39	21995.32	20994.96	17315.42	20790.14	20423.39	20491.49	17217.91
***ETCU* of model B**	26377.63	28383.97	29284.82	26883.18	22076.67	24714.19	23850.23	23470.78	21108.93
Cost savings(%)	29.50	24.27	24.89	21.90	21.57	15.88	14.37	12.69	18.43
Average of cost savings in all of the instances (%): 20.35									

Tab. 6. Cost comparison between Models A and B

	E(S)	E(QC)	E(H)	E(M)	E(SC)
Model A	157.51	16120.07	2761.11	2837.34	116.87
Model B	41.44	17017.88	605.36	14070.68	605.36
Cost savings(%)	-280.02	5.27	-356.10	79.83	80.69

Tab. 7. Range of model parameters in the sensitivity analysis

parameter	value	h	n	l	T	$ETCU^*$
p_i	[45 22 10]	0.95	7	1.66	7.13	12156.64
	[60 30 20]	0.88	9	1.80	3.97	13454.85
	[70 60 50]	0.47	6	1.76	3.32	14101.62
Q_{out_i}	[180 150 250]	0.88	1	5	3.98	13311.15
	[300 250 400]	0.88	9	1.80	3.97	13454.85
	[600 620 510]	0.53	9	1.70	3.99	13633.57
C_{pm}	500	0.72	1	4.87	2.15	11883.23
	2000	0.88	9	1.80	3.97	13454.85
	4300	0.77	8	1.74	5.77	14889.95
C_{fa}	70	0.88	8	1.61	3.97	13449.90
	100	0.88	9	1.80	3.97	13454.85
	450	0.89	13	2.46	3.999	13474.91

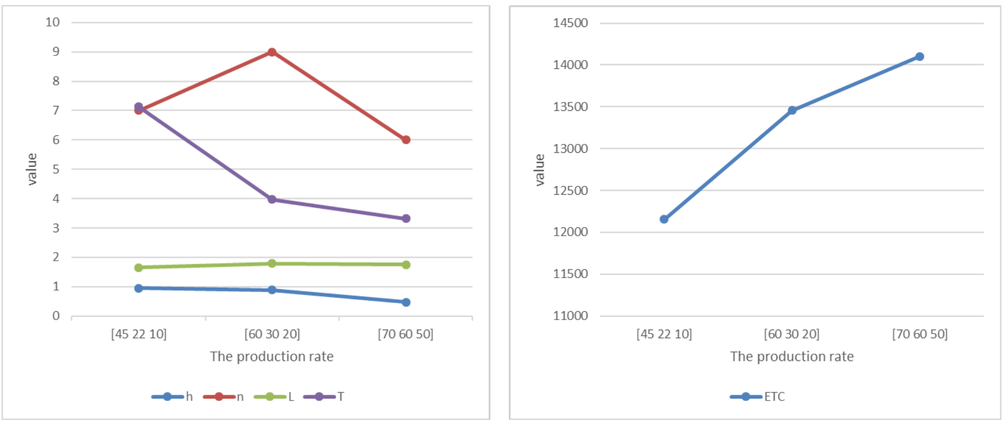

Fig. 11. Effect of p_i on the model output

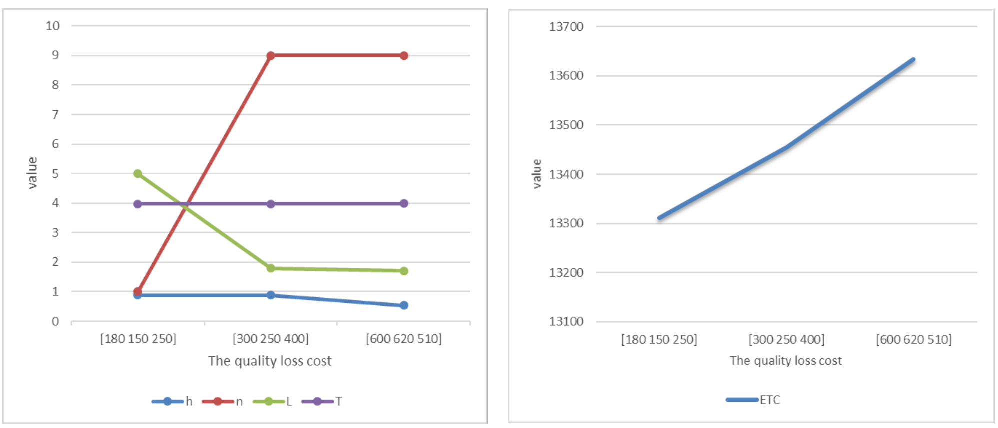

Fig. 12. Effect of Q_{out_i} on the model output

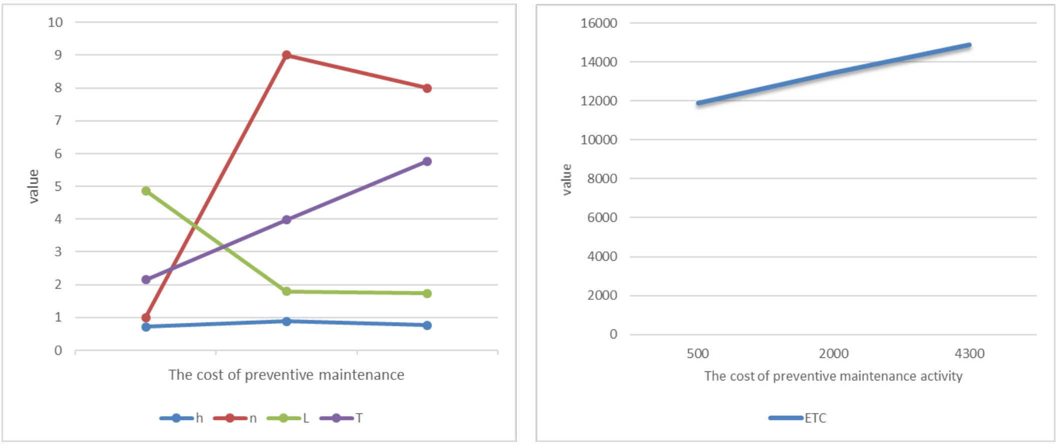

Fig. 13. Effect of C_{pm} on the model output

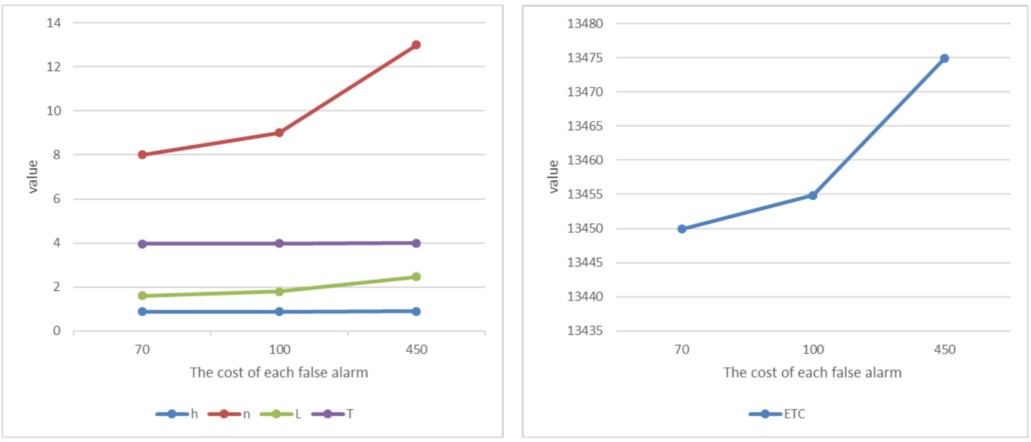

Fig. 14. Effect of C_{fa} on the model output

consecutive subgroups increase when C_{pm} increases from 500 to 2000 and then decreases when C_{pm} increases from 2000 to 4300.

4) As shown in Table 7 and Fig. 14, a slight increase in $ETCU^*$ can be observed since large values of C_{fa} lead to more maintenance-repair costs. However, in contrast to p_i, Q_{out_i} and C_{pm} the dependency of $ETCU^*$ on C_{fa} is not significant. In addition, compared to the other parameters, C_{fa} has a non-linear impact on $ETCU^*$. It can be also concluded that T and h are the least affected variables by variation of C_{fa} .

The obtained results allow for summarising the practical implications of the proposed model, which can be employed by industrial practitioners to optimise the efficiency of their manufacturing systems.

- Integration of maintenance, inventory control, and quality engineering decisions leads to significant cost savings in comparison with making such decisions separately. It is remarkable that the greatest effect of implementing a simultaneous decision-making policy is achieved from the reduction in the set-up cost. Moreover, the maintenance and quality costs are the most affected cost terms by replacing the simultaneous decision-making policy with the separate one.
- In practice, as the value of Q_{out_i} increases, it becomes more necessary to detect the out-of-control condition as soon as possible, which can be achieved by increasing the control chart power as well as reducing the time interval between two consecutive samplings. It should be noted that the control chart power can be improved by taking larger samples and choosing small values of the control limit coefficient. Therefore, in industrial systems, where the production of non-conforming products imposes a significant cost to the manufacturer, it is vital to take larger samples, reduce the time interval between two

consecutive samples, and reduce the distance between the upper and lower control limits.

- In situations when stopping the production process leads to a significant cost for the company, the control chart should be designed so that the probability of issuing an out-of-control alarm under the in-control condition is reduced as much as possible. In this situation, quality practitioners are advised to use larger values for the control limit coefficient to avoid a high false alarm rate.

Conclusions

On the one hand, multi-product systems consist of expensive and complex equipment, and consequently, it is crucial to maintain them in a suitable operational condition by implementing efficient maintenance activities. On the other hand, it is essential to detect process anomalies quickly to satisfy customer expectations and reduce the production rate of non-conforming items by designing statistical quality control techniques. To make more interactive decisions, this paper aimed to integrate three concepts of SPM, maintenance, and inventory planning, for the multi-production processes. The PSO evolutionary technique was implemented to solve the optimisation model and obtain decision variables. The accomplishments of the study displayed that the proposed simulation has better performance for multi-production systems with respect to economic criteria in comparison with the separated model. A comparative study in which 27 different states of inputs were examined based on the Taguchi design of experiment (DOE) method to calculate the cost saving due to different states of input data. The measure was used for comparison between the suggested mathematical model and a separated model. About 20 per cent of cost savings were observed due to the integration of the effective parameter, which almost happened due to the reduction in maintenance and quality cost. Besides, a sensitivity analysis was designed to track the change of results due to four model inputs; the production rate of the product (in one production cycle), the cost of quality per unit when assignable cause occurs, the preventive maintenance cost and the cost of each false alarm. Results demonstrated that the rate of production and the PM cost have significant direct effects on.

The proposed model was established based on some assumptions, such as the normality of the quality characteristic of interest, single-machine production system and the occurrence possibility of only one type of assignable cause, which can be reasonable in small and medium production systems. However, in large and complex industries, such assumptions may not be true. Therefore, to bring the proposed model closer to practice, future studies need to consider multiple assignable causes and multi-machine (parallel or serial) systems. Moreover, developing control charts without the normality assumption of the quality characteristic of interest can be fruitful for future research.

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An approach for semi-automated data quality assurance within BIM models

Steven Cann Abdul-Majeed Mahamadu
Abhinesh Prabhakaran Krzysztof Dziekonski
Rotimi Joseph

ABSTRACT
Successful Building Information Modelling (BIM) enabled projects that require large volumes of project data to be embedded within BIM models. However, with this wealth of data, relevance and accuracy have been identified as important issues affecting the BIM performance of the project. Currently, Quality Assurance (QA) in the industry has focused on geometric data, including scrutinising physical and spatial clashes. However, as BIM practices progress in the industry, the requirements for non-geometric model data and their quality have become more necessary. This study aimed to ascertain the feasibility of using visual programming for semi-automating the BIM QA process in a practical case study on using BIM in infrastructure projects. This paper outlines a generic semi-automated QA methodology and its application in a construction project case study. The validity of this method was tested and evaluated in practice through (n=2) workshops. The methodology was implemented within an integrated engineering consultancy, employing visual programming methodology to generate QA summaries and additionally highlight model elements with data quality issues based on a defined set of parameters. Based on the evaluation findings, the proposed process was feasible and provided a pathway for low-cost and low-skill QA of BIM model data within the architecture, engineering and construction (AEC) industry. The paper's main scientific contribution is a conceptual framework for using visual programming to achieve automatic quality assurance.

KEY WORDS
building information modelling, data quality assurance, model

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Abdul Majeed Mahamadu

University College London, United Kingdom
ORCID 0000-0001-7757-8562
Corresponding author:
email: a.mahamadu@ucl.ac.uk

Steven Cann

University of the West of England, United Kingdom

Abhinesh Prabhakaran

University of the West of England, United Kingdom
ORCID 0000-0001-9049-9148

Krzysztof Dziekonski

University of the West of England, United Kingdom
ORCID 0000-0001-5396-8582

Rotimi Joseph

University of Brighton, United Kingdom
ORCID 0000-0002-2634-8246

Introduction

Globally, the architectural, engineering and construction (AEC) industry continues to embrace a digital workflow, including Building Information Modelling (BIM), which continues to mature and grow in terms of application and adoption (NBS, 2016, 2017). The exponential growth of BIM over the past decade represents a paradigm shift for the AEC industry away from a 2-D drafting-centric approach to 3-D parametric and data-centric modelling (East-

Cann, S., Mahamadu, A.-M., Prabhakaran, A., Dziekonski, K., & Joseph, R. (2022). An approach for semi-automated data quality assurance within BIM models. *Engineering Management in Production and Services, 14*(4), 114-125. doi: 10.2478/emj-2022-0034

man, 2011). In the UK, this shift can be partly attributed to governmental support, mandating BIM use in the UK's public sector projects since 2016 (Cabinet Office, 2011), which has been furthered by the BIM recognition as the key driver in attaining the Construction 2025 goals for the AEC industry (HM Government, 2013). This support and endorsement from the government and industry relate not only to the ensued modelling practices but more to the ideal of a wealth of project information existing in a single accessible database and interchanges (Saxon, 2016).

To date, this shift within the AEC industry has resulted in collaborative BIM workflows and processes, utilising the coordination of multi-disciplinary models, and led to measurable benefits relating to time, cost and planning (Ghaffarianhoseini et al., 2015). Therefore, digital data is becoming a key focus for projects and within the industry as a whole. However, as BIM processes and clients mature, the requirements and volume of BIM data associated with models and projects become greater. These data requirements can be considered relative to two main factors. First, they are, in part, due to the current progression in the application of BIM for facility management purposes (Teicholz, 2013). Whereby the as-built digital asset/model is gaining importance, becoming a key deliverable on projects (Carbonari et al., 2018) and also prerequisites for attaining standards, such as ISO 19650 and other globally accepted standards like Construction Operations Building Information Exchange (COBie). Second, with BIM processes becoming a standard practice for many companies, there is a further internal requirement to refine and standardise model data, be it specified by the client or not, to ensure continuity and a high-quality digital output asset, removing an element of risk from the project (Laakso et al., 2016). Subsequently, to further BIM progression within the AEC industry, it is evident that the need for quality-assured BIM model data and the move towards refined standardised models requires additional attention (Howard & Björk, 2008), given no standard procedures currently exist. Currently, there are several approaches offered by commercial software through integrating Business Intelligence (BI) tools to support BIM data analysis. While some of these tools could support Quality Assurance (QA), their use can be costly and so there's a need for other low-cost solutions that can be implemented from standard BIM and open-source tools.

This study, therefore, aimed to ascertain the feasibility of using visual programming for semi-automating the BIM QA process in a practical case study of using BIM in infrastructure projects. The study further proposes a computational logic and conceptual framework for using visual programming for BIM QA focussed on non-geometric data. The study used widely available tools to highlight the requirement for QA of BIM model data within the AEC industry. The methodology was then tested using a case study project within an integrated engineering consultancy. The designed QA process follows a semi-automated computational workflow and is generic in nature, therefore enabling a feasible, low-cost, low-skill and easily adaptable alternative to current manual QA methods. The paper is structured as follows: a literature review outlining the research background is followed by a literature review of the domain. The adopted research methodology is then described, followed by research implementation, which includes the case study adopted for testing. The primary research conducted for validation is then summarised, followed by a discussion and conclusions section.

1. Literature review

Batini and Scannapieco (2016) identified a key principle by distinguishing the difference between information and data. Information is usable and can stand alone as an individual entity, and data has the prerequisite to be ordered with like terms or requires association with a system or object. To this extent, it is clear that given the parametric modelling technique that BIM embodies, associating attributes to individual elements, the information included in models with an incorrect or poor association is of little benefit and non-representative of clear model data or BIM processes. According to a review of current industry practices by Davies et al. (2017), similar problems surrounding the partial or restricted sharing of BIM models can also lead to data clarity issues. Furthermore, Sun et al. (2017) gauged these issues surrounding data and standardisation within the top four most frequently discussed limiting factors hindering successful BIM application across the AEC industry. Subsequently, the topic and importance of correctly defining owners' information requirements are currently gaining attention in the industry and research (Cavka et al., 2017), highlighting a clear need for model data to be useful, manageable and fit-for-purpose, following predefined formats.

Additionally, as concepts of "Big Data" and the "Internet of things" are gaining considerable attention from the AEC and other industries (Scaysbrook, 2016), it is critical that model data-related issues are addressed, enabling interoperability between systems without compromising data loss. Stricter standardisation mechanisms could be put in place to reduce and eliminate model data-related issues, although internally, companies have the immediate ability to reduce this issue by adopting model QA process workflows.

1.1. BIM model information

Two data types are associated with parametric model elements when considering BIM model information in relation to QA. Kensek and Noble (2014) detailed these as geometrical data relating to the geometry and the associated area of elements and non-geometrical based elements with associated attribute information. The value of this incorporation of both data types within a modelling environment has been the long-standing key benefit of BIM (Azhar, 2011). However, as the AEC industry progresses and BIM adoption becomes more widespread, the true potential of the non-geometrical associated attribute information is becoming recognised, particularly for facility management purposes (Lee et al., 2016). Therefore, accounting for this model after use, with the additional consideration that non-geometrical data issues are not prominently visible within the model environment, there is a greater need for quality-assured model data.

1.2. Level of Detail (LOD)

Within BIM modelling practices, the Level of Detail (LOD) represents the section of geometrical data contained within the model. Two clear subdivisions of LOD data should be considered with regard to model QA. First, as detailed by Fai and Rafeiro (2014), they are the geometric graphical representation of elements within the model environment, increasing in detail relative to higher levels. Alternatively, as explored by Donato et al. (2018), they are the sub-set of LOD data, which surrounds the spatial requirements of model elements, relating primarily to maintenance requirements and safe working zones. Consequently, this enables the possibility to quality-assure the model for both hard physical element clashes and soft spatial serviceability clashes.

1.3. Level of information (LOI)

The non-geometrical information contained within BIM elements constitutes the model's level of information (LOI). The correct association of attributes to model elements enable various high-end BIM opportunities to optimise the design and construction process. Most notably, these include operational and energy performance uses (Lee et al., 2016; Peters, 2018). However, data standardisation issues for a model element, outlined by Hjelseth (2010), still form a key barrier to the wider implementation of BIM, even with continued work to refine element data specifications (NBS, 2018). This can be partly attributed to the diverse nature of projects and consequential data parameter needs. However, irrespectively, this places model data QA as a key feature in future BIM practices.

1.4. Level of development

Currently, the relevance of data, as highlighted throughout this background research, is a key BIM model requirement within the AEC industry. Data relevance can be considered dependent upon the desired output. According to Cavka et al. (2017), employers' information requirements need to enhance this process by stipulating desired model data outputs. In considering this relevance of model data, both geometrical LOD and non-geometrical LOI data require specification. Within the AEC industry, this is known by an inclusive term of the level of development (Boton et al., 2015). The level of development, ranging between standardised values of 100–500 with associated requirements (BIM forum, 2017), can relate to the project stage and model progression, but ultimately, it concerns clear client requirements and specifications relative to the perceived model after use. A clear example of the level of development and data relevance can be demonstrated by Motawa et al. (2013), where the key relevance was attached to the desired functionality of the maintenance-orientated BIM model and element attributes relating to the task number and operation outcome. As demonstrated by this example, there would be little benefit in vast amounts of non-maintenance-based information as this would not fit the model's purpose.

1.5. Current industry quality assurance practice and limitations

Having illustrated the need for model data QA within BIM practices, it is important to note that there are software applications currently in use within the AEC industry. Arguably, the most prominent is Navisworks, as a QA application, which is utilised primarily for checking physical clashes between geometric elements in multi-discipline coordinated models (Autodesk, 2018). However, Holzer (2016) introduced a more advanced rule-based tool, the Solibri model checker, which allows potential risks to be reduced by the automated detection of design deficiencies (Solibri, 2018). Additionally, as an Algorithmic rule-based tool, Solibri enables QA options for the associated spatial requirements and tolerances for elements, accounting effectively for the management of all geometrical data.

Model management applications, such as Kinship (Andekan, 2018), represent the final subgroup of model data QA tools. These tools enable the interrogation of model data on a higher level, focusing on model families, file size and designer access rather than model element attributes to locate modelling errors over the project timeline. Furthermore, whilst not primarily focused on QA within the design and delivery phases of a project, a fair amount of QA work and research has been conducted within the AEC industry to compare as-built conditions to BIM model information. However, this relates more closely to geometrical construction accuracy rather than model element data, utilising either point clouds or photogrammetry to highlight and gauge discrepancies between the as-built conditions and the intended BIM model (Kalyan et al., 2016; Han et al., 2015). Other works have relied on ontology to propose the QA process for BIM (Doukari et al., 2022; Doukari & Motamedi, 2022). The previously outlined current tools, whilst beneficial, relate closely to geometrical QA and do not fully accommodate model data quality needs regarding model element parameter attribute information, thus providing validation and the motive for the study presented in this paper. Although studies like Häußler and Borrmann (2020) considered the role of semantic data in BIM QA, the approach towards automation still requires further development. Some tools have become available for integrating BIM with business intelligence (BI) and data visualisation platforms. Whereas these can be applied for some data QA, they remain costly and offer little automation in terms of bidirectional communication with the BIM process.

2. Research methods

Given the background information, there is a demonstrable need for low-cost, automated QA for BIM, particularly for non-geometrical data. This method is envisioned to be used across the design phases, with further application prior to the project handover. Development and trialling of the designed QA process took place at an integrated engineering consultancy within the structural department, utilising a range of complex to simple projects across varying sectors. An example of the BIM Model used for testing the approach is presented in Fig. 1. QA process took place at an integrated engineering consultancy within the structural department, utilising a range of complex to simple projects across varying sectors (Fig. 1).

2.1. Research design

The proposed method sought to develop a semi-automated computational workflow as an alternative to manual methodologies for QA in a BIM process.

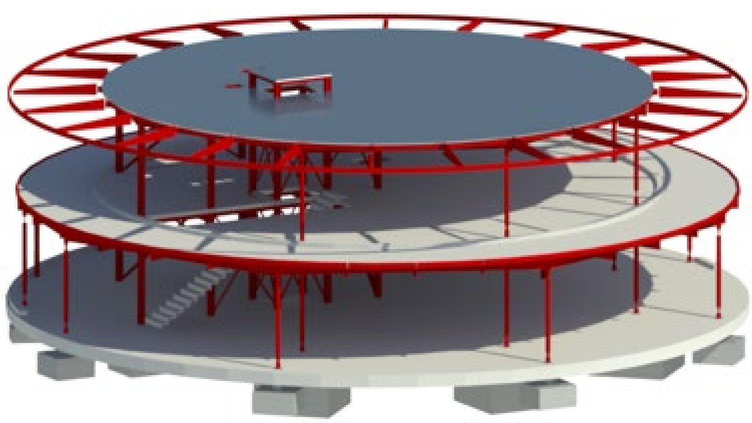

Fig. 1. Low-complexity steel frame community building

The focus on QA in this study was the identification conformance of attached information and parameter attributes associated with structural BIM model elements on a project model during design stages. First, a computational framework was developed and implemented in a visual programming workflow. The method was then tested on a case study of a community building project within an engineering consultancy. The approach and case study results were then validated through two workshops with BIM experts. Similar to focus groups (Creswell, 2013), the workshops allowed the elicitation of industry expert views on the utility and usefulness of the proposed approach while collecting feedback for improvement. Similar approaches have been adopted for testing processes and tools in the BIM domain (Mahamadu et al., 2020). Furthermore, the proposed approach followed up-to-date and current industry progression towards design automation and computational data extraction through rule-based modelling and visual programming (Preidel et al., 2017). The proposed approach was designed to be iterative in nature due to the live dynamic nature of BIM workflows on projects. Therefore, a feasible QA solution must be repeatable, which entails simple process execution reaching a specified format output. A repeatable QA process was achievable, taking inspiration from Preidel et al. (2017), who utilised visual coding to create element constraint queries to check particular variable conditions for validity. The designed QA process in this study incorporates a similar visual coding approach but utilises a workflow, including coded macros within a Microsoft Excel template to format and generate data summaries. The process is outlined in Fig. 2 below.

The tools deployed in the development of the QA process (Fig. 2) were considered due to their availability within standard BIM software (e.g., Dynamo in Autodesk Revit) or wide availability (e.g., Microsoft Excel and Visual Basic). This process eliminates the need for additional programming or plugin complexities in the project workflow (Kensek and Noble, 2014), consequently providing an accessible low-skill and low-cost solution for all users.

2.2. Research implementation

Whilst the designed method included a clear focus hinging upon visual programming to generate the desired output, the implementation of this methodology required specific parameters, workflows and data manipulation techniques, all of which are detailed and examined in the following sub-sections of this study.

2.2.1. Shared parameters

To account for the lack of standardisation and uniformity regarding native parameter attributes within Revit model families, a company/project-specific workflow was followed, allowing parameters to be inserted within all element families. The QA pro-

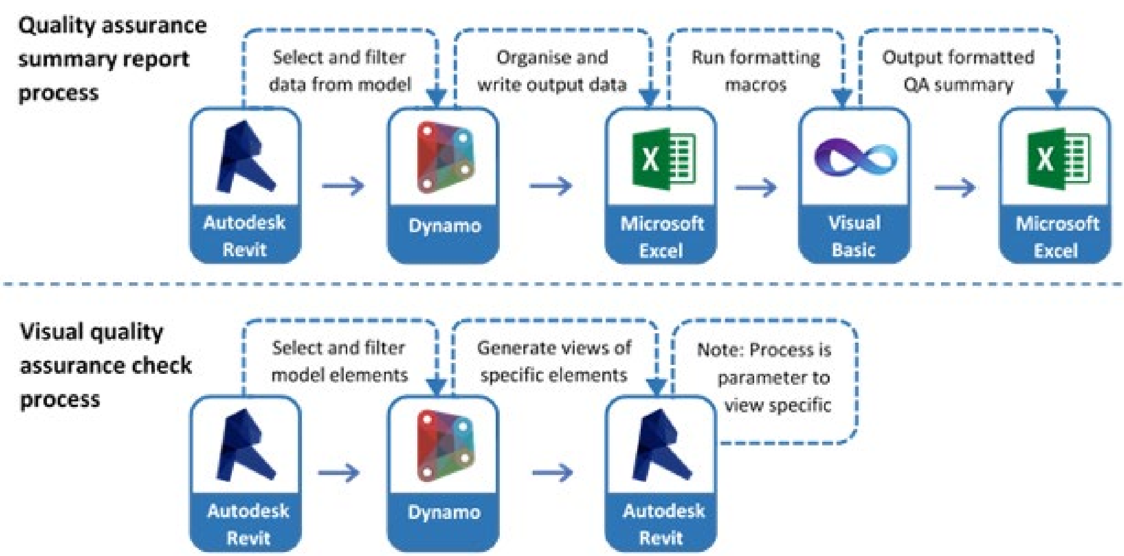

Fig. 2. Process for automated Quality Assurance and reporting for BIM model data

cess then removes ambiguity by ensuring all model elements are adequately included as specified by the company/project requirements (e.g., Employer's Information Requirement). The automation is then implemented for information extraction from the BIM model and then subsequently summarised in a spreadsheet for further analysis. The analysis is used to determine missing parameters and a number of model elements with misaligned information that do not conform to specifications. The total number of occurrences of missing parameters or inadequate information entries can also be ascertained. The five parameters included in this study form the foundation of the QA summary output. The adopted case study was based on structural engineering aspects of a project, thus primarily based on structural elements of the case study BIM model. The included parameters were materials information, LOD, associated model reference levels, element status and material grade (Fig. 3). The methodology thus serves as a filter within the BIM model through visual programming to collate all parameter values for further analysis. The tool can be adapted to accommodate different information or shared parameters.

2.2.2. Process workflow

The presented QA process method was designed with two clear goals, primarily, the summary report on parameter data and the provision of a secondary visual check process in the BIM model. Thus, there is bidirectional communication of extraction, analysis, and summary in the spreadsheet. The summary of the output is presented through visual colour coding of the geometric elements in the model. The primary output was considered to be the generation of a summary report which compares parameter values with what was expected in company requirements on the BIM modelling. This approach ensures that the iterative QA process can occur at predefined intervals following, e.g., the RIBA plan of work stages (RIBA, 2013).

The secondary process of developing visual checks within the modelling environment, as presented, enabled issues to be visually located within the model, enabling faster issue resolution and increased model efficiency. The described workflow process (Figs. 2 and 3) details the linear movement of model data between software applications. Whereby data was extracted, formatted, and output in a Microsoft Excel format to a predefined macro-enabled template. This workflow was used to replace a traditional manual approach to the QA of model parameter data. The approach follows a similar workflow to that presented by Peters (2018), utilising the operability between Dynamo and Microsoft Excel. Lastly, to ensure user accessibility of the QA process, an implementation guide was incorporated into a summary template with the addition of Visual Basic coded formatting macros incorporated as function buttons.

2.2.3. Computational logic

The following equation (1) summarises the approach for computing information quality in the proposed framework. Model Information Quality (MIQ) is expressed as the summation of all elements identified with missing parameter values as a percent-

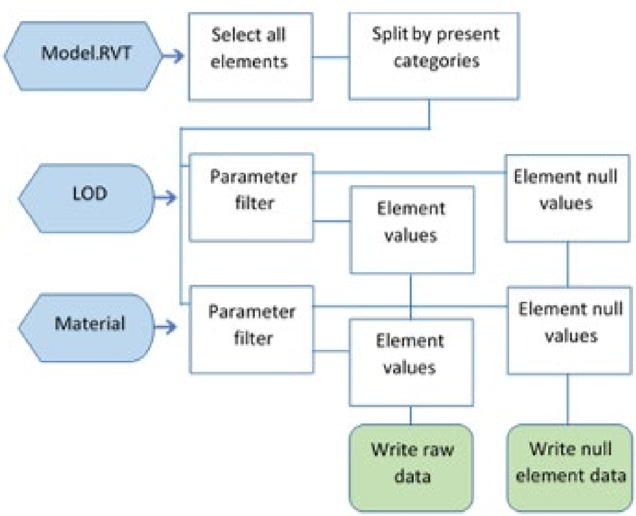

Fig. 3. Process workflow for model-to-Microsoft Excel data extraction

age of elements with required parameter values. In this study, the parameters of interest were: Material Grade, Material Type, Object Status, and Object Level and Level of Detail (LOD). This was assessed in relation to floors, generic model elements, stairs, columns, foundations, structural frames and walls. Equation 1 can be applied to assess information quality for any element or information of interest based on the number of missing key information/parameters detected for each model element.
Where MIQ is the overall model information quality, MI_0 represents instances of missing information or parameters for the relevant model element, and MI_1 represents instances where information exists as specified for the relevant model element.

2.2.4. Semi-automated data quality assurance process in visual programming

$$MIQ = \sum_{i=1}^{n} \left(\frac{MI_{0i}}{MI_{1i}}\right) x\ 100 \qquad (1)$$

Visual programming, which has gained popularity in the AEC industry, enables bespoke activities or functions to be performed within the parametric modelling environment Revit (Kensek, 2014). Furthermore, as suggested by Preidel et al. (2017), visual programming methods are far more intuitive and error-tolerant as opposed to text-based programming languages, allowing ease of adaptability to workflows. In the case of the presented study, the open-source visual programming interface Dynamo, which is now part of standard BIM software (i.e., Autodesk Revit), was used to extract and filter specific parameter data from all model elements, including representation for null values, supplying and writing the raw data to the QA summary template file (Fig. 3). This process required definition from the input of the BIM model by means of the previously examined shared parameters, ensuring the correctly detailed parameter is present in both model and visual programming graph.

Adaptability was further accounted for in the method, in which the Dynamo graphs were constructed, concurrent with best practice policies of companies and the industry, and the use of title captions and colour coding was employed (Fig. 4). Consequently, this increased the level of user confidence regarding possible editing requirements due to the intuitive nature of the method.

Given that the generation of the summary documentation is the primary output of the QA process, the designed visual programming graph consisted solely of "out of the box" or standard nodes, thus eliminating the requirement to download or ensure additional node paths or navigate custom-made coded nodes. The secondary process of creating visual checks within the parametric modelling environment required additional nodes from the Archi-lab package due to limitations within the standard nodes.

2.2.5. Data manipulation

BIM model data was primarily extracted and manipulated within the visual programming environment; however, due to the volume of data, Microsoft Excel provided more powerful and repeatable data manipulation options. The option instilled into the QA process followed a similar data manipulation

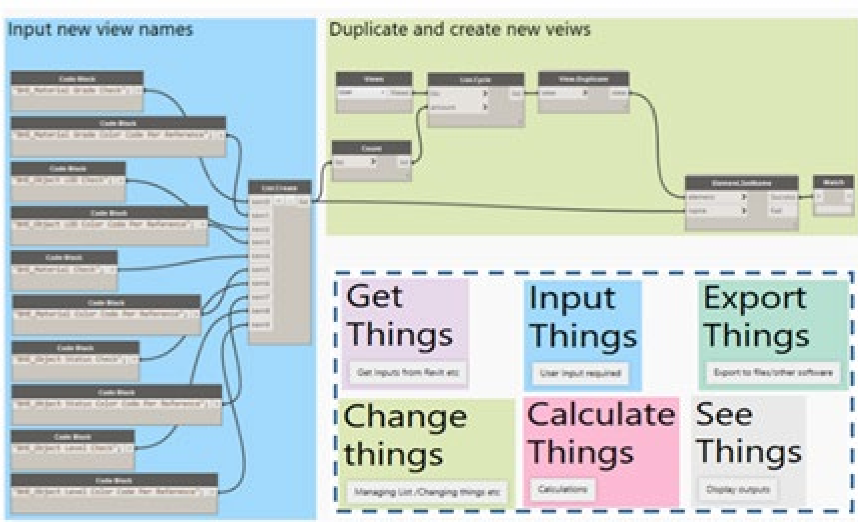

Fig. 4. Example of a Dynamo visual script and colour coding adopted for the organisation of scripts

technique adopted by Khaja et al. (2016) to automate a transfer of data between BIM models and facility management systems through the incorporation of Visual Basic for Applications (VBA) macros. Within the QA process, macros written in the VBA code performed the function of selecting, conditionally formatting and creating summary totals for the multiple parameter data sets, accounting for the variable number of model elements. Assigning the macros to function buttons within the template provided an in-built level of guidance and instruction for users, reducing technical ability as a requirement.

3. Research results

The outputs of the model data QA process are detailed in this section of the paper. They relate to the two separate sub-sections of the designed QA process, the primary output of the summary report and the secondary output of the visual check. The presented specific results relate to the steel frame community building (Fig. 1).

The main summary report output is shown in Fig. 5 and was designed to graphically outline the overall number of complete and null value model element parameters in charts in a spreadsheet. Within the summary, the number of completed values is also broken down into a parameter-specific output. As an additional output, the LOD required within BIM documentation is computed and outlined as shown in Table 1. The output shows a count of model element categories with reference to their respective LOD conformance. This summary is then used and returned to the BIM model to provide a visual understanding of QA relative to each element. The output from the secondary visual check QA process (Fig. 6) shows model elements with completed parameter values from the generated view. This process is parameter-specific, with a separate view being created for each of the five previously outlined shared parameters. It is also important to note that in the

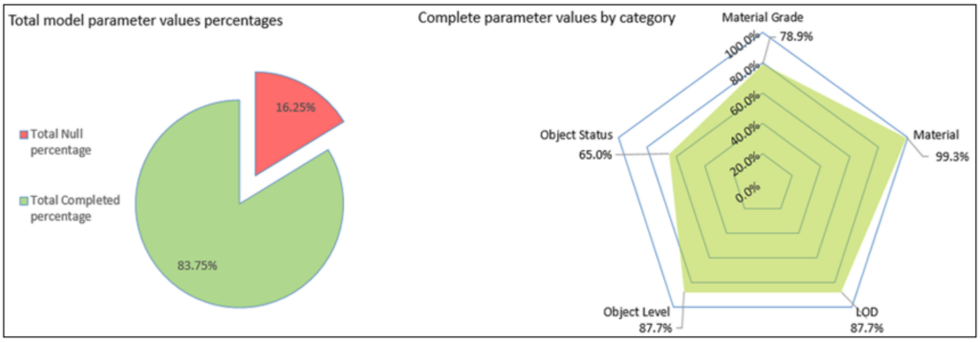

Fig. 5. Overview output of the QA process graphical summary

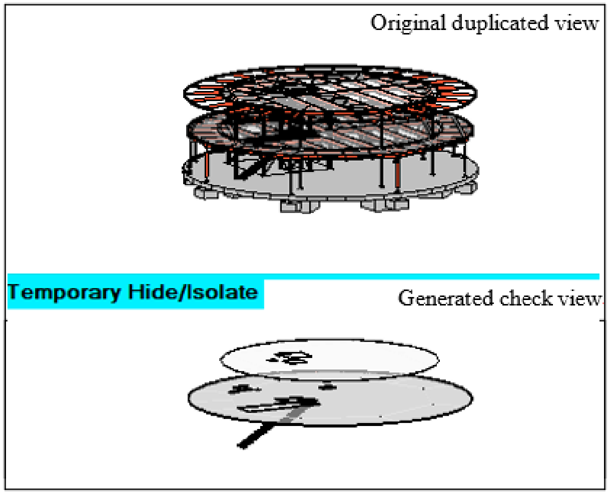

Fig. 6. Visual output of the QA summary in the BIM model

Tab. 1. Model category by LOD classification summary

Model category	LOD Null	LOD 100	LOD 200	LOD 300
Floors	0	13	11	0
Generic Models	3	0	0	0
Stairs	1	0	0	0
Structural Columns	0	0	0	77
Structural Foundations	85	13	39	0
Structural Frame	0	40	0	377
Walls	0	67	0	0

Tab. 2. Workshop participants' views on QA methodology usefulness and relevance

	Theme of validation	Summary of participant sentiments	
		Workshop 1	Workshop 2
1	Relevance to practice	↑	↑
2	Usefulness for the industry's needs	↑	↑
3	Ease of application	↑	↑
4	Ability to enhance continuous improvement	↑	↑
5	Usefulness of results (presentation)	↑	↑

Key: ↑ - Positive; ↔ - Neutral; ↓ - Negative

generation of the QA summary report, project information was automatically read from the BIM model cover sheet and written to title blocks and a relevant project details sheet and the QA summary report.

The proposed method was validated in two workshop sessions with a mix of BIM academics and professionals (n=10 and n=25). The QA process presented functions well and provided clear, useful deliverable outputs generated across a range of steel and concrete framed structural projects of varying scales, primarily educational and commercial projects. Based on the industry's feedback, the QA process is practical, useful, immediately applicable, and relevant. The recommendation suggested applying and testing the approach on a range of other specialised projects, especially complex and larger Mechanical Electrical and Plumbing (MEP) models. Also, further development areas were proposed, including incorporating the baseline benchmarking or recommended values for model data to better quantify and further validate the QA output data.

Workshop feedback was qualitatively analysed with participants representing the academia and external industry BIM professionals. Findings indicated that wider applicability requires tailoring the methodology to incorporate industry-wide data protocols, including UNICLASS and COBie, as part of the computational process to ensure a more generic application to most BIM scenarios. However, the process was deemed "a sound solution for quality assuring BIM model data, improving efficiency and in turn the model delivery process" [the workshop participant's quote]. From the analysis of the responses and feedback, the participants were generally positive about the cost-effectiveness, practicality and user-friendly nature of the proposed QA. The comments were recorded during a thematic analysis to present overall sentiments about the usefulness of the proposed QA method. The three main sentiments were positive, neutral and negative, which were ascertained through thematic analysis as shown in Tab. 2.

4. Discussion of results

Current industry practices regarding the QA of BIM model data are extended primarily to geometric clash-based issues. Additionally, applications surrounding spatially-based constraints are becoming more prominent within industrial processes, installing a further level of QA into projects. However, the literature reveals the need for further research regarding the implementation of QA processes for non-geometrical model element data.

In the case of this paper, the key driver behind designing the model data QA process was design-information efficiency and reliability, partially due to the multi-disciplinary nature of the associated company. However, there are clear alternative benefits to quality assuring model data surrounding facility management and energy modelling options (Lee et al., 2016; Peters, 2018). Furthermore, given standardisation issues related to model element information parameters highlighted by Hjelseth (2010), there is a need to check model information to ensure its relevance to the intended purpose. Given the diverse nature of the AEC industry, the requirements of model data need specification from the employer to ensure fitness for purpose.

The designed QA process sought a generically applicable substitute to current manual-based methods within an integrated engineering consultancy. The method applied throughout the development was one semi-automated computational process reducing the workload and possible errors induced by the reviewer. Given the computational nature of the process and its current, versatile application within the industry, the application of visual programming, Dynamo, was used to extract desirable predefined element parameters. As Preidel et al. (2017) suggested, a primary influence in the application of visual programming for the QA process as opposed to text-based coding was due to its intuitive nature in design and possible future adaptation. The generic QA process, which was designed using only standard BIM tools, accounts for all model categories but would require editing to accommodate additional parameters.

Whilst model data was extracted, initially formatted and exported using the visual programming application Dynamo, post formatting and summary generation used Microsoft Excel. VBA macros were linked to the QA summary template as function buttons. This method was considered given the powerful data manipulation abilities embedded within Microsoft Excel due to the variable scale and the number of model data sets.

As a consideration for further work, the QA process set out in this paper could be easily envisioned and developed into an Application Programming Interface (API) for Revit, removing the requirement to move between Revit and the visual programming application of Dynamo. The detailed QA process consisted of two clear outputs in the form of summary documentation and a visual check generated within views in Revit. Of these, the auditable documentation is of key importance in accessing the data contained within model element parameters. This was achieved by generating completed element parameter percentages on three levels: a model level, a parameter level and a category level. It is important to note that the produced summary results relate solely to data entry within a parameter and does not account for the accuracy of the data. Therefore, if data was provided manually, there is an element of error introduced into the QA summary generation process. The next logical step in the development of the QA summary would entail further work to incorporate model element parameter look-up tables to verify the validity of the extracted model data. Additionally, linking employer information requirements to the LOD data generated within the QA summary would make results clearer. The secondary QA process output of the visual check within the Revit modelling environment provided a quick assessment of areas or categories of model elements with parameter data-related issues. This enabled intuitive parameter editing and correction, installing increased efficiency within the iterative QA process.

Although some methodologies and tools have been developed for BIM QA in practice, there are fewer conceptual propositions on how it can be achieved (Doukari et al., 2022; Doukari & Motamedi, 2022). This study provided a scientific pathway by proposing an equation that can be practicalised using a visual programming approach with the validated and presented conceptual framework. The proposed approach extends previously prosed concepts, including ontology-based methods (Doukari & Motamedi, 2022), towards a more practice-oriented approach.

Conclusions

The research described in this paper proposes a viable solution to QA of BIM model data within an integrated engineering consultancy with a presentation of novel expression as well as an approach to visual programming that can be universally adopted using BIM software. Given the methodology followed, using only standard BIM tools, the presented process is a feasible and cost-effective option for widespread development within the AEC industry. The implementation of a QA process for model data, as outlined in this paper, would not only improve the modelling efficiency but also more effectively accommodate future facility management and energy modelling requirements. A methodology has been presented as well as a framework for using visual programming to achieve the developed mathematical expressions. One of the key advantages is the generic nature of the proposed framework, which allows for modification depending on information requirements for each practice or project scenario.

This research was conducted in conjunction with an integrated engineering consultancy as a result of operational desires to further incorporate computational BIM into work processes and background research. The background research highlighted a lack of standardisation within BIM model element parameter data and a growing requirement for this data to be quality assured as the AEC industry and BIM practices progress in meeting future needs. Therefore, while designers must have the ability and knowledge to deliver BIM models to a high standard, moving forward to future practices and subsequent applications within the industry, the level of data assurance will become a key aspect of project delivery.

The key contributions are as follows:

- There is a growing requirement for BIM data QA within the AEC industry.
- There remains a gap in standards for information quality definition as well as benchmarking.
- Moving forward towards future BIM practices, a greater level of standardisation needs to be agreed upon for information definition as well as benchmarks of quality relative to prescribed levels of information. A novel computational logic and conceptual framework have been proposed based on the development and testing of visual programming approach for BIM QA.
- The application of a semi-automated QA process is a feasible option using standard BIM tools.
- Visual programming represents a key area of advancement for the AEC industry, allowing clear data manipulation abilities.

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