A Service-Oriented Autonomous Crane System

Guangyu Xiong, Petri Helo, Steve Ekström, and Zhen Shen

***Abstract*—The servicing of crane systems has been a major problem in the crane business value chain. The crane industry has been exploring well-defined solutions to solve problems on the customer's site. The service-oriented concept, empowered by artificial intelligence (AI) technology, has shown advantages in addressing issues in manufacturing. In this study, the authors propose a novel crane business model for the crane industry: a service-oriented autonomous crane system, which integrates advanced management concepts and AI-powered technology into the traditional industry-crane system. With the help of the novel business model, the crane industry and customers/users can benefit from an improvement in crane performance, and the model also offers further potential to promote problem-solving in the crane industry on the customer's site. From the perspective of knowledge development, this study gives a clear description of an intelligent service-oriented crane system. Crane stakeholders can develop their own customized autonomous crane systems based on the novel model with its technical structure. From the perspective of strengthening the crane business, the proposed model provides the foundation for developing smart solutions for the crane industry according to the specific requirements. From the perspective of scenarios applied to large construction machinery, the case study in this article provides a valuable reference for augmenting the servicing of large scale construction machinery.**

***Index Terms*—Artificial intelligence (AI)-powered technology, crane business value chain (CBVC), service-oriented autonomous crane system, service-oriented concept, social manufacturing concept.**

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I. Introduction

CRANES are an important part of general construction machinery, and are one kind of traditional lifting equipment. A crane system can be used to lift heavy loads, and place them in a defined area with the help of a set of basic components, including a hoisting mechanism and supporting control system. Because crane systems are widely used in manufacturing, transportation, construction, energy, and harbors, various types of cranes have been developed for diverse industrial sites accordingly. On the customer site, safety and reliability are the most important factors, which reflect in the productivity and efficiency of crane operation and maintenance together with convenience. Various demands shape the characteristics of crane systems. Due to the application environments and customers' regional markets, crane manufacturers have to provide well-engineered solutions to satisfy customers/users. This unique characteristic has produced widescale complexity for the crane business. The crane industry not only delivers the ordered product with well-defined solutions for operation, but also provides user-friendly solutions for maintenance. Therefore, a comprehensive and systematic solution for crane service has also been a key challenge for all crane manufacturers.

A. Research Problems

Autonomous crane systems have been expected to satisfy demands from both the crane industry and customers/users customers in recent years. However, the specific requirements for cranes as construction machinery and the technical barriers crane systems must overcome have plagued both the industry and the academic world, including how to deploy resources in the crane business chain and how to use new technology to support the service process, from suppliers upstream to customers/users downstream [1], [2]. Fortunately, along with the development of the service-orientation concept [3] and its extended concepts in product-service systems (PSS) [4], [5], and social manufacturing (SM) [6] with artificial intelligence (AI)-powered technology plus advanced algorithm [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], it is expected that traditional problems can be solved. In particular, the large and complex nature of the crane and smart solutions for service on site have been a subjects in focus for both the crane industry and customers/users. In recent years, the extended PSS concept-Smart-PSS—has been expected to lead to improvement in both the product life cycle management of the crane and customers'/users' satisfaction [16], [17], [18]. In fact, in recent years many industries as well as academia have been trying to

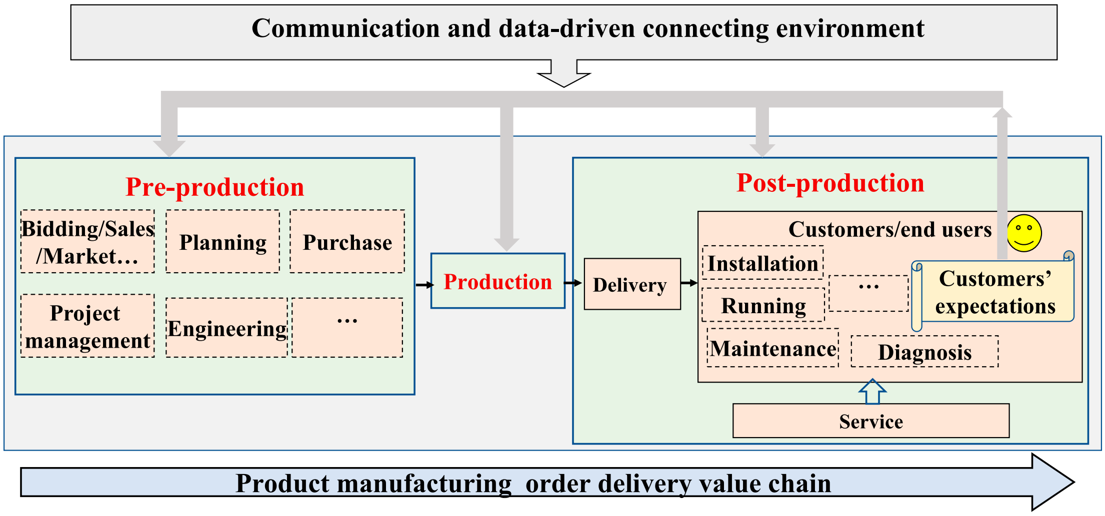

Fig. 1. Manufacturing focused process for customer order delivery through business value chain [23].

solve some of the traditional problems with the help of AI-powered solutions and Smart-PSS approach [16], [17], [18], [19], [20], [21], [22], [23].

From a business value stream perspective, for most industries, the major business process in the business value chain (BVC) is shown in Fig. 1, illustrating how a product is delivered from the manufacturing process to the customer site [23]. Regarding the crane industry, most common issues are from the preproduction stage, that is in solution design (product engineering and configuration), and after-sales service in the postproduction stage, which we call maintenance in this article. Three central problems arising are most likely to happen at the postproduction stage in the crane business value chain (CBVC) and reflect in crane performance. These problems are as follows.

1) Regarding crane operation: The most common issue is related to the crane system maintaining consistent operation in terms of safety and productivity. The major problem is normally reflected in antisway, positioning, protection function, and people-machine collaboration, etc.
2) Regarding crane maintenance: The most common issue is related to the efficient service resource from involved crane stakeholders (see definition in the section on method) supporting on-site maintenance in real time. According to the Smart-PSS concept through the product life cycle, efficient maintenance service on site is another major problem in the after sales process.
3) Regarding the increased customization needs of crane customers/users, the most common issue both crane manufacturers and customers/users face is how to sustainably provide improvement by applying continuous improvement and consistently provide an optimized solution for customers/users through e-service.

The above problems/issues may not cover all problems in the current crane value chain, but they point out the major areas of concern and problems that have always occurred, and these problems could also be associated with most crane stakeholders (CSs). This study focuses on the most common problems in the crane industry that occur on the customers' site. A major motivation of the study is to explore a well-defined solution to help the crane industry solve the major problem of service on site and in real time to satisfy both the crane industry and customers/users.

In short, the objective of this study is to propose a novel model for an intelligent crane system focused on the customers' site, called SACS. A major novelty of the study is that the proposed model not only focuses on the service-orientation to satisfy both the crane industry and customers/users, but also attempts to develop a basis for providing a comprehensive e-solution for problem-solving on the customer site in real time.

B. Contributions of the Study

The major contributions are as follows.

Service-oriented autonomous crane system: the proposed novel crane business model SACS takes into account the service-oriented concept, integrates advanced management ideas like the Smart-PSS approach and value chain concept, supported by AI-powered technology. The SACS provides overall intelligent serviceability for the autonomous crane system. From the perspective of strengthening the crane business, the SACS will also provide the foundation for developing smart solutions for the crane industry according to specific requirements. From the perspective of scenarios applied to similar machinery, the crane belongs to large construction machinery that requires well-engineered solutions. Traditionally, the harsh environment of crane operations always presents more difficulty on site compared with other machinery, so that this study can increase the knowledge on smart technology applied to large construction machinery through the novel model applied to similar machinery used in similar environments.

Benchmark from application in the crane industry: in implementing SACS, this study sets a meaningful benchmark from the real crane industry. In particular, some ideas of the SACS concept are from our ongoing research project, some of which have also applied practical aspects of intelligent autonomous ability to improve the performance of crane systems. The results from the case study provide a benchmark for smart solutions implementing SACS according to the Smart-PSS idea in areas also outside of the crane industry.

The remainder of this article is structured as follows. Section II comprises a literature review of existing work. Section III introduces the research method. Section IV presents a description of the service-oriented autonomous crane system, including a definition of SACS and its intelligent capability, then a structure of SACS is established to show its main composition and intelligent functions. In Section V, some cases of best practices related to the application of SACS are introduced. In Section VI, a conclusion is outlined with the key findings, highlighting the practical implications of the study, and suggesting further research topics and potential development.

II. Literature and Related Work

In this section a review of literature relevant to the existing work is presented. The review reflects on attempts by scholars and the crane industry to solve the issues presented in the introduction and methodology sections of the article. As crane issues are mostly related to the postproduction stage of CBVC when the crane equipment is on the customers' site after sales, the discussion begins with key technology that affects the efficiency of operation, such as the crane control approach that directly impacts crane operating, and service model that impacts maintenance. In addition, due to the limitations of traditional technology and business models, we move to the development of AI-powered technology for autonomous crane systems presented in existing work. Finally, a gap is pointed out between current work and expectation of the development of relevant research topics, wherein the value of the contribution is situated.

A. Related Research Work

Due to key problems mostly happening on site and impacting performance in terms of safety, productivity, and efficiency of operation and service process after sales, we illustrate the relation between major problem areas, crane performance, and the focus of current work from scholars including management approach, empowered technology such as AI-powered technology, system/process/function, and performance. As shown in Fig. 2, the management approach and technology support have a significant impact on system/process/functions of the crane; and the output of system/process/functions directly reflects in the crane performance.

Most existing research relates to improving the performance of crane systems. According to the focus of this work, scholars in recent years have proposed two major streams of work, as summarized in Table I. The first stream is from the perspective of management in considering how to deploy management approaches in systems/processes/functions on site in order to improve crane performance. The second stream is from the

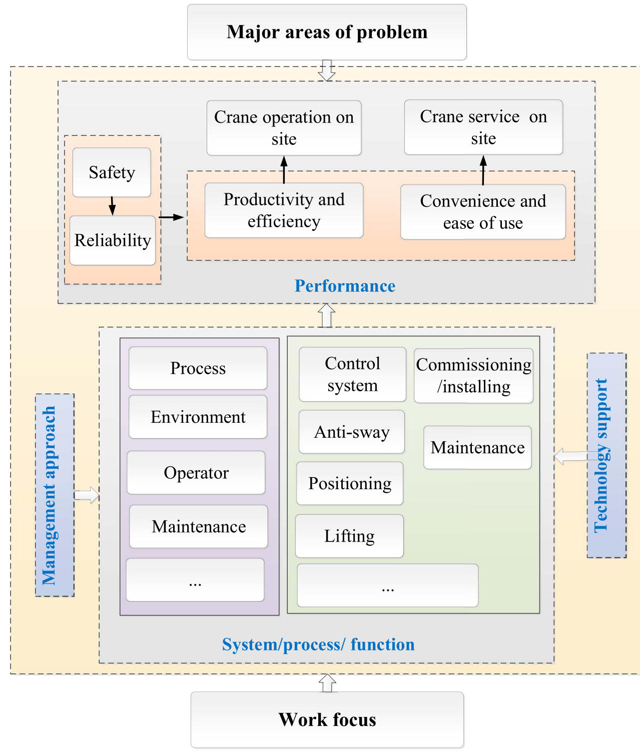

Fig. 2. Major problems, crane performance, and focuses of improvement.

perspective of technology-powered applications in considering the integration of software applications and technology-powered hardware units. Amongst these, normal technology is applied to an advanced controller to improve the autonomous crane operation system. Then, along with the development of AI technology, a new trend in recent years from the second stream is more focusing on specific solution. The new trend integrates advanced management approaches with AI-powered technology for smart product, which is the basis for autonomous crane systems. The goal of producing a specialized solution is the same, that is, improvement in crane performance, such as in safety and efficiency on site, and ease and convenience in operation and maintenance for the crane manufacturer and customer.

As Table I shows, the first stream on management approaches has attracted the attention of some scholars, for instance in applying CI to improve safety and reliability, which are the most important factors on site, and very crucial for the performance of all cranes [24]. Shin et al. state the need to define adequate regulations for industrial sites in order to improve safety, and propose a revision of the standard guidelines such as in accident prevention measures [25]. Zhou et al. propose an effective management model to improve the safety of tower cranes, which is based on a systems thinking approach [26]. The work of Zhou is related to both management approach and performance focus. Zhou et al. used a problem solving method to identify nine major dimensions of the safety system based on analyzing the characteristics of the tower crane safety system components, and developed improvement measures accordingly. Shin et al. and Zhuo et al. have tried to apply the CI approach based on

TABLE I
REVIEWS OF TWO MAJOR STREAMS OF RESEARCH WORK

#	Class	Literature	Research Focus	Contribution to Crane System
1	Management approaches	Shepherd et al. [24]	Focus on how continuous improvement (CI) effectively improves crane performance for crane systems	Improve safety and reliability
		Shin et al. [25]	Focus on adequate regulations for industrial sites, and proposal for a revision of the standard guidelines based on RCA	Improve safety
		Zhou et al. [26]	Focus on how the proposed management model based on CI for cranes based on analyzing the characteristics of crane safety system components	Improve safety and its measures
		Sadeghi et al. [27], Jinwoo et al. [28], Kan et al. [29]	Focus on how to implement appropriate crane management effectively to achieve relevant management goal by extending safety factor	Improve safety based on avoiding potential hazards
2	Technology-powered application	Yoon et al. [30]	Focus on a developed dynamic simulator that can reduce accidents for mobile cranes based on data analysis	Improve safety by reduction of crane accidents
		Omar et al. [31]	Focus on a new designed fuzzy logic controller.	More robust control system for crane.
		Kawasaki et al. [32]	Focus on an autonomous mobile overhead crane system	Improve control system and implement antisway, road obstruct recognition and path planning
		Chen et al. [33]	Focus on the intelligent ability of crane operation based on the proposed definition of intelligent crane	Improve operation performance of crane system
		Smoczek et al. [34]	Focus on the method of control system with fuzzy control and pole placement	Application for contactless measuring of sway, and capturing stereo images of crane position in operation
		Zhao et al. [35]	Focus on developing a monitoring system applying IoT technology to monitor operating in real-time	Improve crane operation in outdoor environment
2 (New trend)	Integrating advanced management approaches with AI-powered technology	Zhong et al. [36]	Focus on application of wireless sensor network (WSN) and IoT for a safety management system with help of remote supervision	Improve operating safety for tower crane groups on the construction site
		Zhou et al. [37]	Focus on a cyber-physical-system-based safety monitoring system (CPS-SMS) applied in the environment of metro and underground constructions, with the help of IoT	Improve operating safety
		Wu et al. [38]	Focus on blockchain technology applied to the safety inspection of tower crane	Improve the effectiveness of on-site safety
		Olearczyk et al. [39]	Focus on iCrane that uses advanced intelligent crane algorithm for crane system in heavy construction operation	Improve customized service, meet various crane customers' requirements on site appropriately
		Ma et al. [40], Sun et al. [41], Smoczek et al. [42], Maghsoudi et al. [43], Rong et al. [44]	Focus on solutions for the issue of swing during crane operation by control strategy and applying AI-powered technology	Improve crane's performance by means of special solutions for antisway
		Han et al. [45]	Focus on a decision support model as a major solution for crane operations	Support solutions considering major customer's requirements
		Ray et al. [46]	Focus on applying 5G and IoT to remote control for steel industry	Improve reliability of crane operation in poor environments
		Autiosalo et al. [47]	Focus on applying digital twin to develop multicomponents for an industrial overhead crane	Improve operating and related work of served CSs in crane business chain
		Huang et al. [48]	Focus on a service schedule optimization solution—MILP model for the scheduling issue of multiple cranes.	Improve efficiency and safety performance for multiple cranes.
		Burkhardt et al. [49]	Focus on a novel graph searching algorithm for path planning procedure	Support of special solutions for path planning for tower cranes
		Zhao et al. [50]	Focus on applying digital twin technology for a hoisting management system framework using Dijkstra's algorithm	Improve accuracy and safety performance on site
3	Application cases of autonomous crane system	[20], [21], [22]	Focus on application on developed service-oriented product for autonomous crane systems supported by AI-powered technology	Improve the performance of operations and maintenance in crane industry by means of AI –powered technology

root-cause-analysis (RCA) [51]. A weakness in both the above authors' research is that the data collection is limited by the geographical area, or equipment types, or lack of consideration of the service model. Their conclusions coming from the system analysis have practical significance for improving the safety of the crane system. Other scholars have also focused on the combination of performance, management approach, and system/process/function in order to improve safety and reliability [27], [28], [29]. Sadeghi et al. [27], Lee et al. [28], and Kan et al. [29] focused more on the safety factor and provided an implementation of crane management. In particular, Kan et al. [29] carried out a review of related regulations and presented an estimation of the safety thresholds according to the website of the occupational safety and health administration (OSHA), in order to avoid potential hazards emanating from management, and system/process/functions in mobile cranes. Yoon et al. [30] developed a dynamic simulator for mobile cranes based on data analysis of crane accidents, in order to reduce the number of accidents and improve safety. The above work focuses on management driven and system/process/function-driven approaches in crane system.

The second research stream is focusing on applying emerging technology to crane systems. Omar et al. [31] presented an autonomous overhead crane operation system with the help of a newly designed fuzzy logic controller. The designed controller was implemented and tested in a small-scale overhead crane, and the result shows that crane operation using the fuzzy controller is more robust compared to a traditional controller. Kawasaki et al. [32] introduced an autonomous mobile overhead traveling crane system that uses a two-degrees of freedom control system in order to avoid the weakness of the feed-forward control system and implement antisway. The proposed system integrates systems with obstacle recognition and path planning, the usefulness of which has been proven in autonomous mobile systems. The above solutions focused on control controlling systems to improve crane operation. The above work focuses more on technology-powered approaches to improve crane systems. Along with the development of AI technology, e-solutions driven by intelligent technology applications in research are increasing. Other scholars have attempted to apply AI-powered technology to improve crane performance, in particular in terms of convenience and ease of service on the customer site. Meanwhile, the research focus extends from the application of intelligent AI technology to related advanced algorithms.

Amongst the research on intelligent crane systems in recent years, the new trend has been in advanced management approaches supported by AI-powered technology. Chen et al. proposed a definition of intelligent cranes [33] from multiple perspectives in intelligent operation capability and configuration of software application and hardware equipment to implement the crane tasks. According to Chen, the intelligent crane is an automatic machinery system in which the various tasks of movement can be completed by means of system and function in automatic control, programming, people-machine interaction, and self-diagnosis. Chen also pointed out that: "the intelligent crane has some intelligent abilities similar as human, including perception, planning, operating, coordination, learning and decision-making." Chen's definition also shows how intelligent ability can drive the intelligent functions of crane operation. Clearly, the emergence of intelligent cranes brings about new possibilities to solve issues in the crane industry and new paths in the development of the industry. From the perspective of the application of AI-powered technology with advanced algorithms, Smoczek et al. introduced an application for a crane control system implemented in the laboratory, which was based on the method of fuzzy control and pole placement [34]. According to the crane control system Smoczek described, a machine vision-based technique was used for contactless measuring of the sway with the presented control algorithm, whilst an untypical stereovision system by means of a single camera was used to capture stereo images of the crane position during operation. Besides the advanced fuzzy control approach, Smoczek's control system adopted more AI-powered technology to improve performance in terms of productivity and efficiency of the crane operation. Zhao et al. developed a monitoring system for hoisting heavy loads in crane operation in outdoor environments, which applied the Internet of Things (IoT) technology in monitoring the system [35]. Their system could monitor the status of operation in real-time. Later, Zhong et al. presented a further application of wireless sensor network (WSN) and IoT for a safety management system [36]. According to Zhong et al., a combination of WSN and IoT was applied for tower crane groups on the construction site in order to ensure operating safety remote supervision. Zhou et al. developed a cyber-physical-system-based (CPS-SMS–based) safety monitoring system for blind hoisting operation in the environment of metros and underground constructions [37]. According to Zhou's proposal, an unsafe status in the hoisting process could be avoided by simulating and monitoring using CPS-SMS. Meanwhile, IoT could also be applied to accident prevention, and CPS-SMS was implemented in real cases successfully. Wu et al. developed a blockchain-enabled framework for tower cranes to improve the effectiveness of on-site safety inspection [38]. According to Wu et al., blockchain technology was applied for automatic safety inspection and recording the status of crane operation by means of providing participants with trustworthy inspection. Wu's solution could not only improve safety inspection, but also ensure the immutability, transparency, and traceability of data, which could provide a basis for further preventive maintenance of the crane system. Olearczyk et al. presented an intelligent crane algorithm for crane systems in heavy construction operation, which was called iCrane [39]. The iCrane could support planning for crane lift on heavy industry sites, by integrating all important aspects into a developed software, such as automation, planning of the crane, and simulation. The developed iCrane algorithm with its application could improve customized service to meet various crane customers' requirements in specific automation and planning on site. The above work took more AI-powered technology into account in improvement or problem-solving on site for crane system.

In terms of the new trend for increasingly customized solutions to specific demands for cranes, some scholars have also attempted e-solutions integrating advanced management approaches and AI-powered technology: for instance, e-solutions for antisway and positioning and accurate positioning or grasping during crane operation, Ma et al. proposed an antisway closed-loop control strategy for the typical issue of swing during crane operation [40]. According to Ma, two feedbacks from trolley moving displacement and swing angle were considered in control strategy, both of which could be measured in real time. Ma's proposed strategy could not only improve the overhead crane's performance by means of solving the issue of antisway, but also provide a basis for a 3-D overhead crane. As antisway is one of the most needed improvements mentioned in the introduction, in addition to Ma et al., other scholars have also provided their own antisway solution from the perspective of control strategy combined with algorithm [41], [42], [43], [44]. Regarding more specific requirements, Han et al. developed a decision support model that integrated the major aspects of solution in design, simulation, and evaluation for crane operations [45]. Han's model provided feasible crane types and approaches by considering the cost and environment on the customer site. Ray et al. applied 5G technology for a developed E-crane solution for the steel industry company Tata (an iron and steel company), where the crane operation had to be in a poor working environment such as in rain [46]. According to their E-crane solution, the 5G new radio waveform could be put together with narrow band IoT for the remote control of live camera and voice in case some accident remedial measures needed to be taken, in order to ensure the reliability of crane operation in poor environments. Autiosalo et al. developed a multicomponent digital twin for an industrial overhead crane [47]. In this, a prototype implementation for digital twin for an overhead crane was built for the designer, maintainer, and operator on the site of the related crane, so that all them were CSs. Therefore, the developed industrial digital twin could improve the operation and related work of the served CSs. Huang et al. developed a service schedule optimization solution for the scheduling issue of multiple cranes [48]. According to their solution, a mixed integer linear programming (MILP) model was used for optimization based on lifting requests, location selection, and sequences of lifting. Huang's solution could improve the efficiency and safety of multiple cranes by means of scheduling optimization. Burkhardt et al. presented a novel graph searching algorithm for path planning procedure in the control of tower cranes [49]. According to Burkhardt, the proposed graph-based path planning algorithm could make a path plan based on the identification of distance, energy, or low exciting load sway paths in order to generate the trajectory combined with an antisway controller. Zhao et al. proposed a hoisting management system framework that applied digital twin technology [50]. According to Zhao, Dijkstra's algorithm was used for hoisting route planning based on data from a building information model. Zhao's work could improve the performance of accuracy and safety on site. The above work was reflected in a Smart-PSS approach with the help of the advanced management concept and supported by AI-powered technology.

Besides relevant academic work, the crane industry has also had contributions from the e-solutions of autonomous crane systems reflected in the Smart-PSS approach and supported by AI-powered technology [20], [21], [22]. Amongst these, TRUCONNECT was developed by Konecranes. With the help of AI, TRUCONNECT offers a series of maintenance services for all connected crane customers (local cranes) in order to improve operational performance in safety, productivity and sustainability, and effective service for maintenance on site, and also take into account the product life cycle [21]. A remote crane monitoring solution for the operation of Heavy Goods Vehicles (HVG) developed by VerveTronics Imagineering offers a solution for monitoring and collecting data on safety alerts, operations, and the movement of cranes, which adopts cloud technology to support remote actions/tasks of the local vehicle [22]. Although these are only examples of the industrial applications of AI applied in the service processes of autonomous crane systems, the application points to future trends in the crane industry.

From the above review, and as summarized in Table I, AI-powered technology can be applied to crane systems to satisfy both the crane industry and customers/users. The goal of all the work focus is the same: that is, the improvement of crane performance on site, in particular ease and convenience of service to the customer. These all point to the need for well-defined crane solutions in terms of service on site in real time.

B. Gaps in the Current Research

A growing body of academic literature shows the strength of AI-powered technology applied in intelligent crane systems, and some applications of AI-powered technology have been developed to improve the service ability in some industrial scenarios. The weakness in current work is the limited development of the intelligent capabilities of the autonomous crane system. From the above review, the key limitations are listed as follows.

1) To regarding a clear understanding of the intelligent autonomous crane system, current work lacks a comprehensive description. Even though Chen et al. proposed a definition of the intelligent crane [33], the description focuses more on the aspects of intelligent functionalities of crane operation, and pays less attention to intelligent service aspects, which is an important stage of entire CBVC.
2) To regarding autonomous ability, most current work has paid more attention to the application of certain parts of technology to partly solve issues, but has rarely considered a comprehensive and systematic e-solution for an intelligent autonomous crane system that provides good service in real time.

The core limitation is the lack of a systematic description of the autonomous crane system, including its major value contribution and supporting technology focused on service process. Our study anticipates that the autonomous crane system will be a smart e-solution for developing an overall intelligent

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autonomous ability by means of integrating AI-powered technology and Smart-PSS concept [16], [17], [18], in order to better address service for customers/users in both operation and maintenance. Different from existing work, the novel proposed crane business model in this study not only completes some defined functions/tasks for a certain aspect, such as control for positioning, antisway, grasping, and diagnosis for safety, but also sustainably optimizes customers'/users' operation and maintenance in the entire crane product life cycle.

To fill the research gap, this study takes service-oriented value into account in the autonomous crane system with the help of AI-powered technology in order to develop a new intelligent autonomous crane system—SACS—to satisfy the crane industry and the demands of the customer. Our study is primarily based on the new trend of second stream, and a more smart/intelligent approach to e-solutions for solving service problems in cranes. We comprehensively take into account the power of the service-oriented concept and AI for service-oriented autonomous crane systems.

III. Method

A. Proposed Method

The study in this article is based on our work from an ongoing project, "New Service-Oriented Business Models and a Sustainable Manufacturing Ecology for the Life Cycle of Smart Cranes," mainly supported by Business Finland, with the cooperation of the National Key Research and Development Program of China. As mentioned in the introduction, the major motivation of the study is to explore a well-defined e-solution to help the crane industry to solve a major problem—service on site and in real time to satisfy both the crane industry and customers/users. To achieve the target, this study needs a deep understanding of the service problems on site and current solutions, and then develop the new business model for CBVC that can fill the gap or limitations of the current way of problem solving. Because the proposed model is novel, its application to a case crane industry is needed in order to verify its effectiveness, so for this reason a case study is introduced and analyzed.

In terms of the problems concerned through CBVC and the product life cycle of the crane, a systematic literature review was carried out for two major research streams. Previous work has shown that AI-powered technology applied to the autonomous crane system can help to solve some issues; however, the autonomous crane system is still immature in existing work, and an appropriate solution is still incomplete, a point made in the previous section. This study follows the new trend of the second research stream—focusing on customer specific solutions that are integrated with AI-powered technology and an advanced management approach. The study adopts a combination of literature survey to review existing work, and qualitative research to define SACS. Then a technical structure for the crane business is presented for implementation of a novel model. A case study is presented to verify the effectiveness of the proposed crane business model. With the case study, the essential ability of the intelligent functioning of the crane system is illustrated and analyzed. To achieve the presented

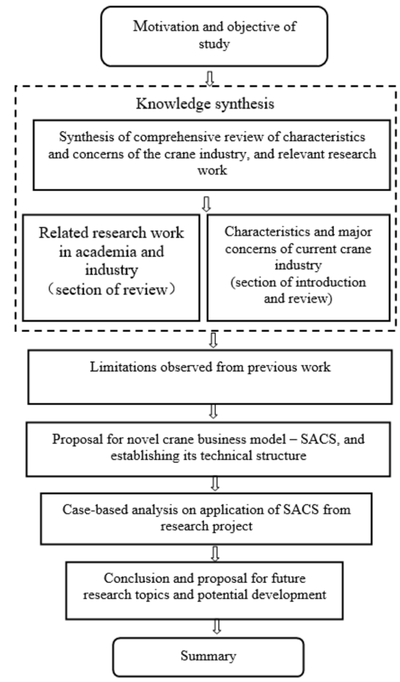

Fig. 3. Framework of the research method.

objective, the research methodology is presented as a process in Fig. 3 and the method includes and is analyzed as follows.

1) Motivation and objective of this study as introduced in the introduction.
2) Exploring the characteristics and concerns of the current crane industry to understand the major problem areas of the crane system based on a comprehensive review of existing work.
3) Presenting an e-solution—the novel crane business model—SACS, with its technical structure based on a service-oriented concept, supported by AI-powered technology.
4) Introducing a case study of best practices that illustrates how the case crane industry uses a smart e-solution for improving the intelligent ability for service on site in order to verify SACS.
5) Proposing possible future research topics and potential development with the accumulation of better understanding in knowledge, application, and development of AI-powered technology.

B. Related Definition

In order to have a better understanding of terms in this study, there is a need to clarify definitions of key terms, which are listed as follows.

Definition 1: Product business value chain is a supply demand network that can include multiple layers of participants who are connected to the chain by business, and which can add value for their downstream participants -customers/users—through a defined business process or activity [23].

Definition 2: CBVC is a business value chain network for crane products or crane systems. It contains multiple crane stakeholders (see definition as below) in different layers, which are connected by the crane business and can add value for their downstream crane customers/users.

Definition 3: Crane stakeholders (CSs) are participants along the CBVC, including the crane manufacturer, main contractor comprising some crane manufacturers, and sub-contractors upstream such as component manufacturers and engineering/design units, and customers or users downstream in the chain.

Definition 4: Product service system (PSS) is a business model based on a value-adding-oriented idea to satisfy consumers/users by means of an integrated system for the delivery of both products and services to meet customers‘/users' expectations [4], [5]. Smart-PSS is an extension of PSS, which is the integration of smart products and e-services into single solutions delivered to the market to satisfy the needs of individual consumers [16].

Definition 5: AI-powered technology refers to innovative technologies and applications using AI, in order to change and impact business with a wide variety of technology associated with both software and hardware units, such as information technology, intelligent computing, IoT, VR/AR/MR/XR, big data, digital-twins, machine learning, deep learning, robotics, blockchain, etc.

Definition 6: SM is defined as a kind of Internet-based and service-oriented advanced manufacturing paradigm covering the whole stages of a product life cycle [6].

IV. Description of Service-Oriented Autonomous Crane System

A. Definition of Service-Oriented Autonomous Crane System

From the perspective of the service-oriented concept of value chain, Smart-PSS concept, and AI-powered technology, our definition of the service-oriented autonomous crane system is as follows: it is a novel service-oriented business model based on a customer-value-centric idea and Smart-PSS concept. SACS is a suite of e-solutions of AI-powered technology integrated with an advanced management approach to crane systems, assembled to improve the service performance regarding operation and maintenance of the crane system. SACS aims to achieve a customer-value-centric intelligent autonomous crane system by minimizing issues on the customer site. With SACS, the assets of local connected cranes and related CSs can enrich important information in real time, associated with crane status, alarm on operation, and preventive maintenance in service, etc., which can reduce or even eliminate issue-handling time in operation and maintenance.

B. Intelligent Capabilities of SACS

Four key intelligent capabilities need to be considered in developing intelligent SACS: intelligent service in operation, intelligent service in maintenance, intelligent control and management, and intelligent connectivity through CBVC, as shown in Fig. 4.

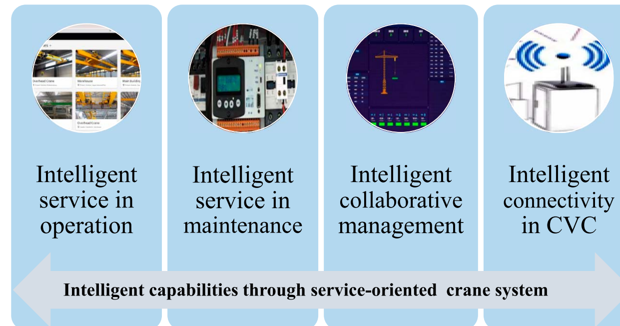

Fig. 4. Key intelligent abilities through SACS.

Four key intelligent capabilities need to be considered in developing intelligent SACS: intelligent service in operation, intelligent service in maintenance, intelligent control and management, and intelligent connectivity through CBVC, as shown in Fig. 4.

In the proposed SACS, we take the service-oriented concept, Smart-PSS, and value chain concept into the novel crane business model, in order to enhance the crane's overall performance. In the intelligent operation a friendly human-computer interface is provided, and the execution of programs for operation is controlled to implement fully automatic cranes with processing set-up.

The intelligent service in maintenance uses AI-powered technology, such as big data technology, IoT, VR, digital-twins, cloud computing, and advanced algorithm to support decision-making and predict and prevent potential failure through a predictive maintenance approach.

The intelligent control and management capability provides a management system for well-functioning process management, information monitoring and transformation, and sustainable development through related CSs involving value-adding for end users in the crane system.

Intelligent connectivity through CBVC enables necessary functions/actions/tasks to be implemented remotely. Intelligent connectivity enables transformational new capabilities in transport, entertainment, industry, and much more. In order for technical systems to match human actions digitally with connected environments, however, they must match the speed of our natural reaction times. The network used must be ultra-reliable, as many critical tasks will be implemented remotely, which should be implemented by means of cost-effective edge infrastructure to enable scaling.

The next sub-section introduces the technical structure of SACS, which not only includes composition levels and elements, but also detail illustrating the reflection of major intelligent capabilities from a technical perspective.

C. Technical Structure of SACS

As the service-oriented concept that emphasizes the customer-value-centric idea plays an important role in SACS, the major process of SACS runs through the crane value chain

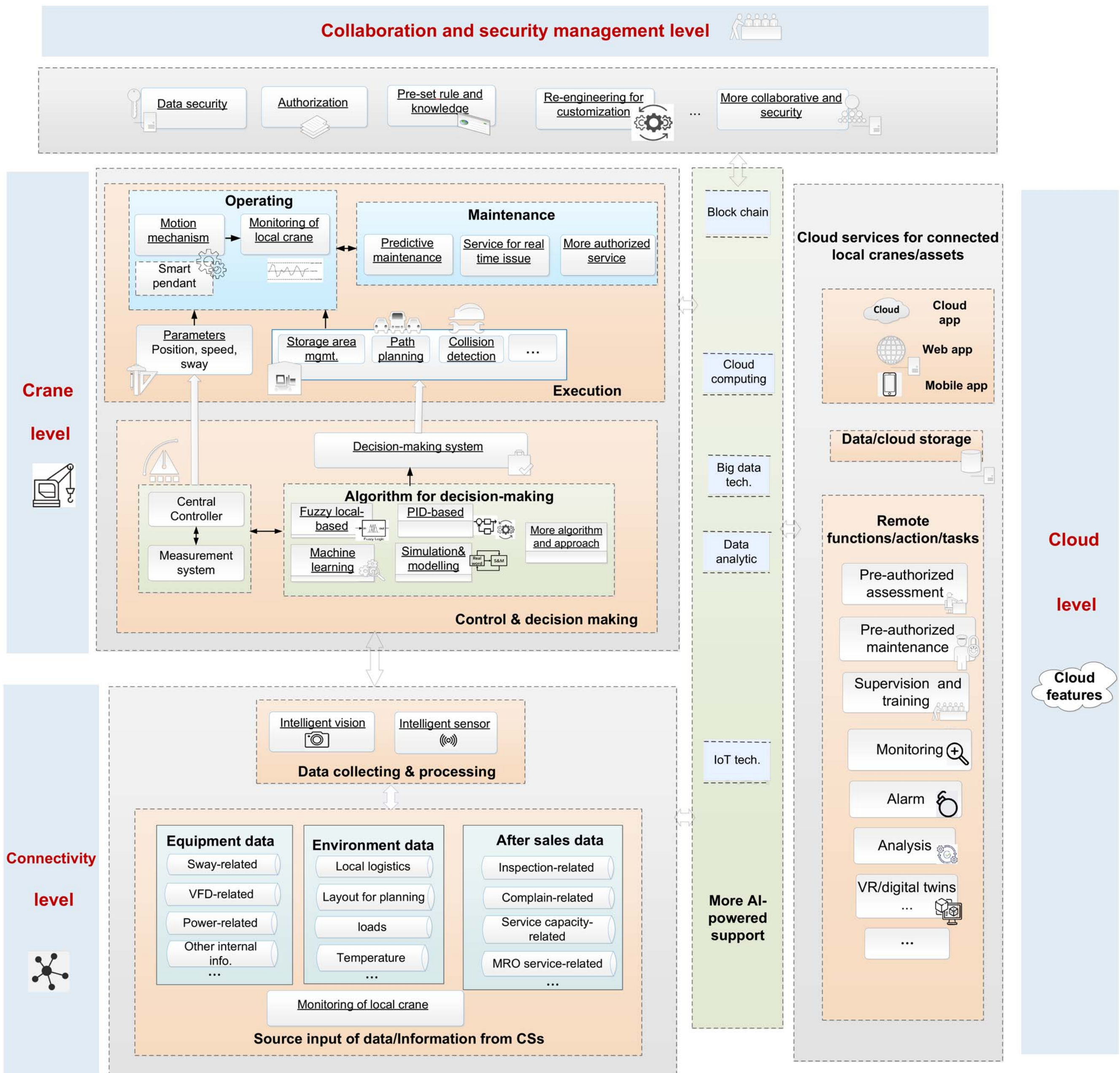

Fig. 5. Technical structure of SACS.

through remote functions/actions/tasks. A technical structure is created in Fig. 5, which provides the basis of an actual implementation of SACS, and its one detailed application is introduced in the next section. Fig. 5 shows that SACS contains four technical levels, which are the cloud level, connectivity level, crane level, and collaboration and security management level.

The cloud level provides cloud-driven functions/actions that can be performed remotely supported by AI-powered technology. This level serves as a platform serving as a medium or platform for data, management, operations, and decision-making between other levels. Through this level, a comprehensive and systematic management approach is defined and adopted to connected local cranes (customers/users). The connected customers/users are able to obtain a cloud-based digital service in real time. The data could relate to customers' assets, operating data, components/spare parts/devices, and people on site. There are three major elements at this level: cloud, data/cloud storage, and remote functions/actions/tasks. There is a need to clarify here that "cloud" used for the cloud level only refers to the applications performing remotely to achieve defined tasks. These include not only cloud applications, but also web-based and mobile-based applications, which can be used as a supplement to cloud applications if feasible. With the related technology of cloud computing, data/information storage and defined remote functions/actions are performed at this level. The cloud functions/actions can be defined and agreed with connected customers/users. Meanwhile, the technology of data analysis and big data are applied to support crane control and decision-making at the crane level for operation and maintenance on site. One important supporting function at this level is remote monitoring. With the help of remote monitoring, remote functions/actions can be reacted to and performed. For instance, from the perspective of service for safety and maintenance and predictive maintenance, preauthorized maintenance, and assessment for some key components/spare parts, safety alarm and important analysis are performed or supervised remotely. From the perspective of CI, continuous supervision for the customer to optimize processes for operation and maintenance can also be included. From the perspective of operation for safety and productivity, loads, positions, brakes, and length of rope are included for computing and analysis in order to support decision-making at the crane level.

At the connectivity level, IoT-based networks are provided that connect data/information from CSs and process collected data/information, with the help of IoT-driven technology integrated with software application and hardware units. There are two major elements at this level: one is the source of data/information from CSs, and the other element is for data collection and processing. In terms of data collection and processing, more intelligent functions can be developed and accessed; for instance, the intelligent sensor and vision units can be integrated in related equipment to support data/information collection and processing. Regarding the source input of data/information, there are three groups of data/information, the first being the equipment data from inside the crane, such as data on sway and position, variable-frequency drive (VFD), and the power of the crane. The second group of data is related to the environment on the customers' site outside of the crane, such as data on layout, and temperature in the environment of the local crane. Some crane-related data come not only from the local crane, but also from other stakeholders, such as manufacturers, contractors or subcontractors who use the necessary data to produce or engineer the equipment or component accordingly. The third group comprises special data for maintenance, such as daily/regular inspection, complaint-related data, service capacity in the system including all stakeholders, and maintenance service-related data/information. All data should be authorized for functions/tasks for the crane system, where authorization is supported at the collaboration and security management level.

At the crane level, the crane functions/actions/tasks are implemented. In order to do so, two major elements are needed at this level. One element contains the control system and decision-making system, which define and input related parameters for the crane operation and support the decision-making, such as in path planning, storage management, and safety issues such as collision detection on site. In this element, the control part consists of the central controller and measurement system. The measurement system is designed for measuring the positions and speeds of the crane's motion mechanism, and the central controller applies the control method to define related parameters for the execution of crane operation, such as in sway, speed, etc. Currently, crane manufacturers use programmable logic controller (PLC) for the control system, and the control method applies advance control algorithms such as fuzzy logic controlling (FLC)-based, or PID-based algorithms to define the appropriate parameters. Both the control and decision-marking parts are developed with software and hardware, and installed into SACS, which is one part of the solution. In terms of the second element, execution, the motion mechanism enables the crane operation. With the help of a remote monitoring system, the status of operation in the crane equipment is monitored, and further maintenance action can be taken accordingly, such as predictive maintenance and preauthorized maintenance. Besides regular maintenance and prediction of the service's function, real time complaints about issues can also be followed and reacted to through remote maintenance if needed. Most major service-oriented functions/actions/tasks should be authorized or preauthorized, which is at the collaboration and security management level and also supported by AI.

At the collaborative and security management level, a practical network security platform is provided, which is responsible for the necessary protocols and collaborative management of connected assets on SACS. As important data/information, resources, and capacity need to be shared with CSs for remote service functions/actions, and to support operation and maintenance for local connected assets, the stakeholder needs the collaboration and security mechanism, which is indispensable in covering all the cloud service functions/actions to act against potential cybersecurity vulnerabilities. In practice, one application could be the application of blockchain technology [52], which can provide data/information security automatically implemented via intelligent contracts between CSs, an and protect the effectiveness of collaboration. In addition, there are also other options to promote collaboration and security, but no matter what mode, coordination and security functions must be included. From a technical implementation perspective, the preauthorization or authorization, data security, predefined rules and knowledge supporting the service function/actions on the local crane can be defined, such as authorization for regular maintenance service. All authorization needs to be updated according to the crane's status with a new agreement initiation. The collaboration and security management level supports most remote service functions/actions for crane operation and maintenance. The CSs apply the service-oriented concept and collaborate with each other to undertake operating and servicing functions/actions for the local crane by following preauthorization, authorization, and new agreements if needed. At the collaborative and security management level, data/information security and effective communication are maintained in order to implement the remote functions/actions in an efficient way.

With the above technical structure of SACS, the crane industry is able to secure an intelligent capability to add service/value for customers/users according to their own specific customization. Under the developed SACS, crane customers/users are able to handle the major issues in operation and maintenance with remote functions/actions/tasks. The next section presents an application from a real case and research work.

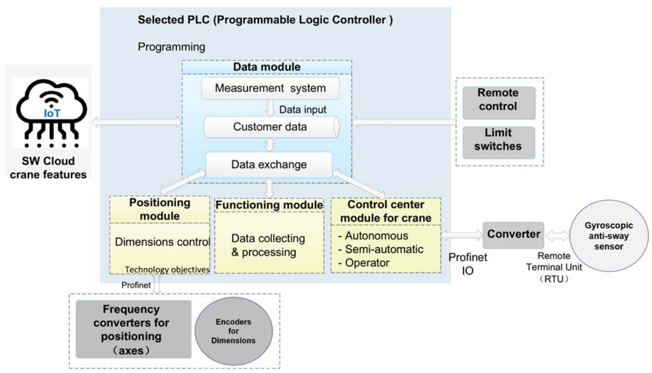

Fig. 6. Structure of the smart crane control system.

V. Application of Service-Oriented Autonomous Crane System

A. Smart Control System for Crane

An application based on SACS has been developed by our sponsor company SW—which has supported our on-going project. The application is a control system developed for implementing SACS for the crane industry with its connected customers, the control system of which is called the smart control system.

The smart control system serves as an e-solution for connected customers (local crane) to meet the needs of service on site in real time. Its major components are structured as in Fig. 6.

As Fig. 6 shows, a selected PLC is used for the smart crane system, and has four modules with key functions, as follows:

1) data module for data input and exchange;
2) function module for data collecting and processing accordingly;
3) positioning module to actuate dimension control;
4) control center module for functioning of control modes for connected customer.

SW is able to use the smart crane control system to provide a set of smart e-solutions to provide service remotely from its control center. The smart e-solution supports connected local cranes in improving safety and productivity with the help of developed cloud features/functions.

With the help of related software applications and hardware units, the intelligent capabilities of autonomous crane systems with service-oriented features can be achieved when enabled by the above modules: in particular, solutions for the special requirements, mentioned previously, include intelligent antisway, positioning, grasping, planning/scheduling, alarm, maintenance in harsh environments, and supporting storage management according to service agreement. These service-oriented features are achieved through the application of SACS.

In Fig. 6, with the connectivity that corresponds to the cloud level offered by the case company, the related input of the data module is from the connected local crane, including related data for operation, inspection, maintenance, and findings which support management for the local customer. The function module collects input data and processes them according to the element of data collecting and processing at the connectivity level in the technical structure, as shown in Fig. 5. The positioning module implements intelligent positions for the crane operation that correspond to the crane level of SACS associated with data processing at the connectivity level and remote supporting at the cloud level. Moreover, an antisway sensor is also developed as a special solution to antisway through a control center module. The control center can affect all levels of structure on SACS, as shown in Fig. 6. With the control center module, three control modes are available for customers to choose for operation on site: autonomous, semiautomatic, and operator-based according to the requirements of local customers, and each control operation can perform motor travel, crane position, and antisway accordingly.

Regarding solutions for the special requirements of customers, the smart control system is able to provide a set of e-solutions for remote service. First, with an antisway algorithm, and embedded in the smart sensor developed by SW, the selected PLC is able to achieve smooth and accurate crane positioning. Frequency converters are used for dimension control for the traveling motors directly controlled from PLC, and a developed smart sensor with embedded smart algorithm for antisway helps the connected cranes to travel smoothly and meet the special requirements for accurate antisway during movement of the crane. Second, customers can obtain their special requirements for intelligent recognition and grasping, and intelligent path planning and positioning remotely. Third, besides operation on site, more value-added service for loading planning/scheduling, storage management, and maintenance is also considered based on the SACS, through remote functions and cloud connectivity, empowered by AI-powered technology, such as IoT, big data, data analytic, VR/digital twins, and cloud computing. These AI-powered technologies link and work together to support the cloud level, connectivity level, crane level, and collaboration security and management level corresponding to the technical structure of SACS, as shown in Fig. 5.

With the remote function, the smart control system in the control center can supervise the connected customer with many functions/tasks on site in real time. Major implementable functions/tasks include the job queue from the factory data-system, position data exchange on time, counting runs, counting services, counting product life cycle, and even energy counting, document storage, management for collaboration, and security corresponding to the collaboration and security management level of the proposed technical structure of SACS, as shown in Fig. 5. More cloud features and remote functions are still being developed, which aim to satisfy future customers with more requirements. All provided cloud services in real time are reflected in solutions for connected local customers: normal operations, special solutions and optimization for management, which are implemented by the smart control system based on SACS.

For executing features, functions, and cloud services successfully, the smart crane control system conducted a series of tests and finally put the results into actual application. Regarding the defined piloting process shown in Fig. 7, two major tests were conducted. First, a test was conducted on a demo crane

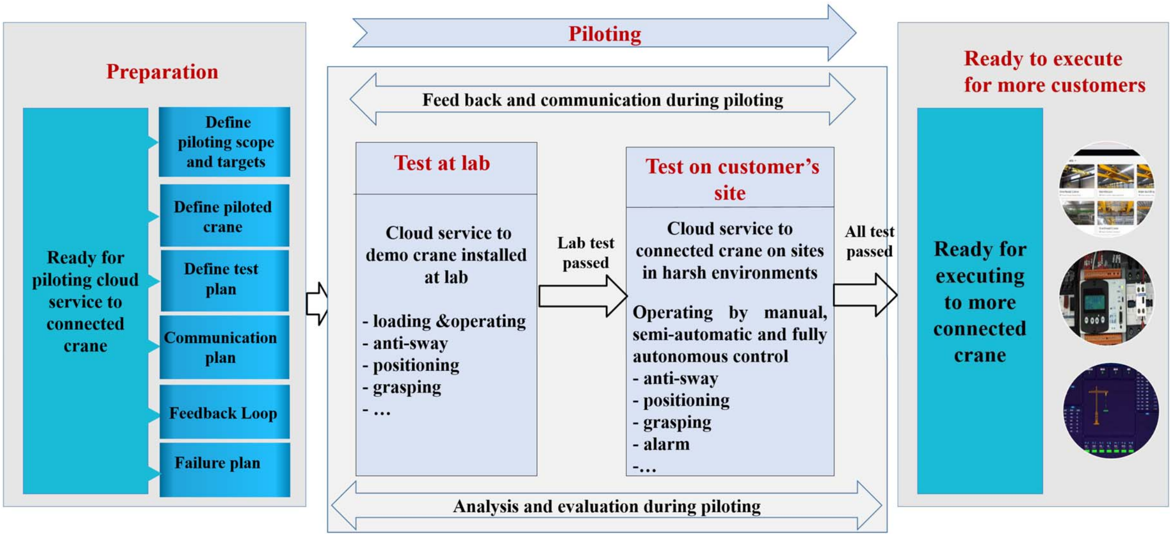

Fig. 7. Piloting process.

installed in the university lab that our project team has been working with. Major features, functions, and cloud services were tested, results were analyzed during the test process, and adjustment and optimization were addressed in accordance with the feedback from the test. Then a more optimized solution was piloted on connected cranes on several European customers' sites in harsh environments. These connected cranes indicated that all cloud service functionality was fully realized.

As the behavior of a system can be measured by defined key performance indicators (KPIs), so the performance of cranes is measured by defined KPIs during piloting, which use a smart control system instead of the old system. The two major KPIs that have been developed take into account the cycle time of automated positioning and Overall Equipment Effectiveness (OEE) of cranes. The definition and calculation of the two major KPIs is as follows.

1) R-CTP: The ratio of improvement of automated positioning of piloted connected cranes; the percentage of improvement of average cycle time (minutes or seconds) daily spent on positioning from piloted cranes (%)

$$\mathrm{R-CTP}\,(\%) = \frac{\mathrm{CTP_b} - \mathrm{CTP_a}}{\mathrm{CTP_b}} \quad (1)$$

CTP: average cycle time for positioning daily

$$\mathrm{CTP} = \frac{\sum \text{Numbers of cycle time spent on all positioning daily}}{\text{Numbers of delivered positioning daily}} \quad (2)$$

CTPb: CTP before the smart control system was applied.

CTPa: CTP after the smart control system was applied.

2) R-OEE: The improvement ratio for OEE from piloted connected cranes within 24 h; the percentage of improvement on average OEE (%) daily from piloted cranes (%)

$$\mathrm{R-OEE}\,(\%) = \frac{\mathrm{OEE_b} - \mathrm{OEE_a}}{\mathrm{OEE_b}} \quad (3)$$

OEEb: OEE before the smart control system was applied.

OEEa: OEE after the smart control system was applied.

OEE: Overall Equipment Effectiveness is an industry standard indicator that shows how a machine, production line or a complete process is performing in terms of asset effectiveness. This research utilizes OEE to examine the crane's process. In theory, OEE calculation is in terms of Availability (A), Performance (P, can be speed, rate), and Quality (Q)

$$\mathrm{OEE} = \mathrm{A} \times \mathrm{P} \times \mathrm{Q} \quad (4)$$

$$\mathrm{A} = \frac{\text{Planned operation time-Unplanned downtime}}{\text{Planned operation time}} \quad (5)$$

$$\mathrm{P} = \frac{\text{Total operation amount} \times \text{Ideal cycle time}}{\text{Planned production time-Uplanned downtime}} \quad (6)$$

$$= \frac{\text{Total operation amount} \times \text{Ideal cycle time}}{\text{Gross operating time}} \quad (7)$$

$$\mathrm{Q} = 100\% - \text{Wasted operation}\,\% \quad (8)$$

In piloting practice, the OEE calculation uses a simplified formula for convenient data collection, and the formula is: value added operation time/planned operation time. Therefore, the OEE calculation is as follows:

$$\mathrm{OEE} = (\mathrm{A} \times \mathrm{P} \times \mathrm{Q})_{\text{theory}} \quad (9)$$

$$= \left(\frac{\text{Valuable operating time}}{\text{Planned operation time}}\right)_{\text{practice}} \quad (10)$$

$$= \left(\frac{\text{Ideal process time} - \text{Wasted operation time}}{\text{Total time-Planned stoppages}}\right)_{\text{practice}} \quad (11)$$

The two major KPIs above reflect the improvement of performance of cranes by using the smart control system. In the piloted cranes, the antisway functionality improved the precision in both manual operations as well as in automated positioning. For manual operations, the safety indicators guided the operators. In terms of the above calculation, automated positioning antisway enabled faster running speeds and thus improved the

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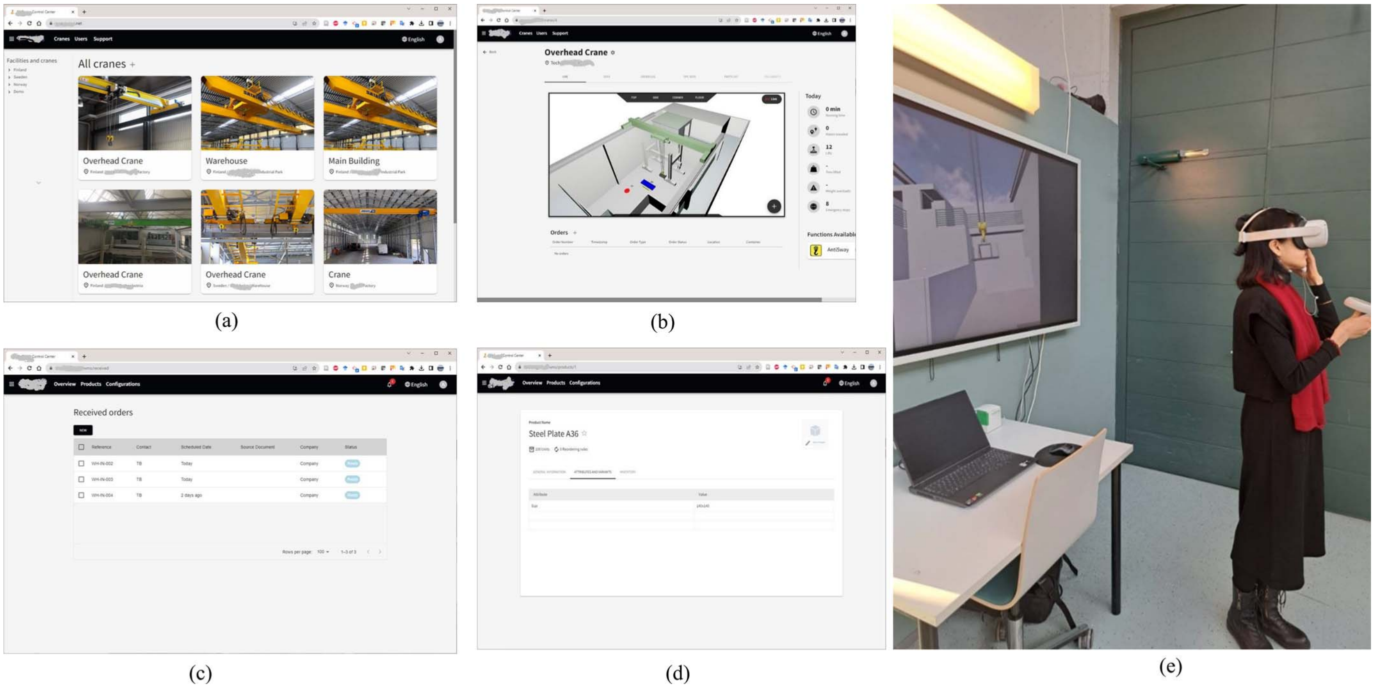

Fig. 8. Example of views of cloud features and functions from the smart control center. (a) Overview for connected facilities and crane showing in the control center on cloud. (b) Overview of customers' orders from one connected crane in Vaasa. The middle view is a 3-D view of facility and connected crane; the right side shows daily status of the connected crane. (c) Service for received orders of storage management (schedule of crane) from connected local cranes in customers' warehouses. (d) Overview of connected customer login in customer portal. (e) VR technology for 3-D experience that can apply digital-twins for simulation of local customers' site in a lab.

automated positioning of the piloted connected cranes by 20% as connected cranes can transfer corrective maintenance actions to preventive maintenance. The OEE improvement was 5–10%. Autonomous features of the crane can provide additional capacity and enable 24-h use.

B. Benefits of the Smart Control System for Cranes

As scenarios both in the university lab and real customers' sites have shown, the smart control system shows that some benefits have been produced, with even more cloud features still under development. Fig. 8 shows views on screen of the cloud features in the control center, including views, as follows;

1) overview from the control center showing connected facilities and crane on site;
2) view of customer orders from one connected crane with 3-D view of facility and connected crane;
3) view on service for received orders of storage management (schedule of crane) from connected crane in customers' warehouse, information of lifted loads/product;
4) overview of connected customer login in customer portal;
5) VR technology for customer experience with 3-D view that applies digital-twins in the lab.

The smart control system is the best practice of the SACS in applying smart e-services to all connected crane customers. Regarding all scenarios both from the lab testing and real customers' sites, the benefits of cloud service from the smart control system are obvious. In particular, with the developed smart sensor embedded with intelligent algorithms for special features such as antisway and positioning, the connected crane benefits from reaching the quickest solution during operation without sway, even when lifting and lowering. This process can be completely automated, so that not only is overall efficiency improved, but safety is also increased. By adopting the smart control system in several piloting scenarios under various environments on customers' sites, strong intelligent capabilities and cloud features can be achieved to improve efficiency for operation and maintenance.

Obviously, the smart control system provides a smart e-solution to help service in operation and maintenance, and for solving problems on site and in real time. The piloting shows that improvement of efficiency can be achieved both for operation and maintenance for connected cranes. In short, the key benefits from the smart control system are listed as follows.

1) Improve performance on the customers' site, both in operation and maintenance, such as in safety and reliability, accuracy and stability, productivity, and responsiveness, through intelligent function, such as antisway, quick positioning, intelligent recognition and grasping, etc.
2) Improve problem-solving, local customer management and CI for crane customers through intelligent service function after sales, such as optimization in planning/schedule solutions, storage management, optimization of product lifecycle service, and security management.

3) Improve remote service to provide more cloud features, through intelligent computing, data analysis, IoT and big data, such as preventive maintenance, and intelligent alarm.

In short, as the service-oriented business model, the smart control system offers service convenience to crane manufacturers, and an improvement in safety, productivity, and sustainability to connected users. It is a smart solution reflecting the Smart-PSS concept. Furthermore, more cloud services/features are under development, aiming to provide smart e-solutions to satisfy the customer and produce possible innovations in service value-adding.

VI. Conclusion and Further Research

In this section, the main contributions of this work are summarized, and directions for future research are pointed out.

A. Conclusion

This study mainly presents the novel crane business model-SACS based on service-oriented concept and supported by AI-powered technology. SACS provides efficient e-service delivery to customers/users, and solves issues quickly on site. Its application to the crane industry verifies the effectiveness and huge potential of the novel crane business model. In response to the major service problems on crane sites, the major findings from this study include the following areas.

First, from the perspective of knowledge development, the study gives the first clear description of an intelligent service-oriented crane system for crane service on site. To fill in the limitations of existing work, this study takes an overall view of the entire crane value chain, and provides a description of an intelligent autonomous crane system that is based on the service-oriented concept, supported by AI-powered technology and a more advanced management approach such as Smart-PSS and value chain concept to strengthen the performance in operation and maintenance.

Second, from the perspective of practical implications, the study provides a technical structure to support implementation of the proposed novel business model, which reflects in the composition and functions of the intelligent SACS. The four levels of technical structure with all elements are integrated to enable autonomous service to the customer (connected local crane). The structure serves as a basis for the crane industry and even extends to other similar large construction machinery in developing customized SACS, and also provides a basic framework for further, deeper research.

Third, the best practice from the application case and ongoing project shows the practical benefits of the novel business model, which is able to offer possibilities of value-adding to service. The results from the application show that the feasibility and effectiveness of the smart e-solution from SACS have both been verified in practice to an extent. The application case not only verifies the novel model as introduced, but also provides a valuable reference for large scale construction machinery in improving service.

B. Future Research

This section suggests directions for future study. From the perspective of service, exploring the innovative service model is still an important topic for existing and future study due to the characteristics of the crane industry. It is necessary to perform deep study on some innovative practices. One of the widespread applications is SM based on the concept of the sharing society, so it would be meaningful to further explore the social services between CSs from the perspective of SM, such as providing social service resources for customers/users. In fact, there have been some attempts, one good practice being a digital monitoring and management platform for an urban construction (DMMPC) piece of crane equipment that has been developed and organized by Ningbo housing and construction bureau, China (NHCB) [53], [54]. More than 10 567 items of various construction crane equipment have been connected to a digital platform, with 869 involved companies and 23 139 operators. There have been more than 3000 construction sites connected to the digital platform up to 2022. The Housing and Construction Bureau in Ningbo has adopted this digital platform at the municipal level, to help the monitoring and management of the industry-construction and lifting industry which are customers/users of CBVC. Besides CSs as defined in the previous section, a third party is involved as a service agency, which means more capacity according to the new manufacturing method—SM. DMMPC provides a useful attempt to use the SM concept for service in the crane business. Therefore, one direction for further research could be in the field of social service for the crane industry. For instance, how the SMR and socialized service resources (SSR) are shaped and optimized to deal with required services on site in the crane value chain, and how SMR service providers arrange the required capability to meet the service performance in delivery, quality, and cost, in accordance with Wang, Jiang, and Xiong et al. [6], [7], [8], [9], [10], [55].

From the perspective of CBVC and different sectors of industry in which cranes are working and cooperating, future research could be focused on how integrated intelligence promotes the overall service ability, and optimizes the total cost of service for the sectors of specific industry and crane classification. For the various sectors of industry that the crane serves, intelligent integration is primarily dependent on the cooperation and common interests of relevant specific industry sector alliances. Meanwhile, the scope of related involved CSs of specific industries should also be defined for implementation. For instance, the case of DMMPC shows that DMMPC can lead the digital platform project in enhancing intelligent service for specific users in the regional construction industry. For more autonomous crane systems, the ability of an integrated intelligence service is primarily dependent on the requirements of various applied scenarios in a specific industry. All these aspects need further in-depth research.

From the perspective of product life cycle, the processes in the upstream stage of CBVC are also important, such as R&D or engineering. The upstream processes are very important in terms of impacting the performance of crane operations, though the processes or stages are not focused on in this article. Further research could extend intelligent ability into R&D or engineering: for instance, the focused topics could be on how AI-powered technology can enable efficient communication and cooperation between the processes of R&D or engineering and crane users, which is also a common issue in the early stages of the product life cycle, or how the SM concept and Smart-PSS can be used in the R&D or engineering process to more effectively utilize various resources and develop e-solutions in the product life cycle.

From the perspective of integrated operation, a one-stop operation could be developed for some scenarios of SACS. Some attempts to adopt SACS in real industry from the case study in this research still need further research for specific application scenarios. For instance, integrated intelligent and autonomous functionality in operation for storage areas could be applied to improve storage management, where the topic could focus on a one-stop operating combination with autonomous recognition and grasping, positioning, optimized path planning, scheduling and storage area management, and antisway controlling for connected crane assets. Other scenarios could be investigated, for example at harbors, amongst others.

Finally, the research on autonomous crane systems could be supplemented with a focus on the behavior of the CSs in the crane value chain, since the chain governor has the biggest impact on the behavior of the crane value chain: how the chain leader affects the intelligent ability of service for crane customers/users, and the service-oriented business model.

The above suggestions could serve as a road map for future research on the topic of service-oriented intelligent autonomous crane systems.

References

[1] "High and lows." *Cranes Today*. Accessed: Oct. 24, 2023. [Online]. Available: https://www.cranestodaymagazine.com/features/highs-and-lows-7864195/

[2] "A challenging market." *Cranes Today*. Accessed: Aug. 15, 2023. [Online]. Available: https://www.cranestodaymagazine.com/features/a-challenging-market-8741463/

[3] F. Jackie and L. Alexander, "Gartner's hype cycle, special report for 2005." Gartner. Accessed: Jul. 15, 2023. [Online]. Available: http://www.gartner.com/resources/130100/130115/gartners_hype_c.pdf

[4] L. Piscicelli, T. Cooper, and T. Fisher, "The role of values in collaborative consumption: Insights from a product-service system for lending and borrowing in the UK," *J. Cleaner Prod.*, vol. 97, pp. 21–29, Jun. 2015.

[5] P. Helo, A. Gunasekaran, and A. Rymaszewska, *Designing and Managing Industrial Product-Service Systems*. New York, NY, USA: Springer-Verlag, 2017.

[6] P. Jiang and J. Leng, "The configuration of social manufacturing: A social intelligence way toward service-oriented manufacturing," *Int. J. Manuf. Res.*, vol. 12, no. 1, pp. 4–19, 2017.

[7] P. Jiang, *Social Manufacturing: Fundamentals and Applications*. New York, NY, USA: Springer-Verlag, 2019.

[8] W. Feiyue, "From social computing to social manufacturing: The coming industrial revolution and new frontier in cyber-physical-social space," *Bull. Chin. Acad. Sci.*, vol. 6, pp. 658–669, 2012.

[9] F.-Y. Wang, "Parallel system methods for management and control of complex systems," *Control Decis.*, vol. 19, pp. 485–489, 2004.

[10] G. Xiong, T. S. Tamir, Z. Shen, X. Shang, H. Wu, and F.-Y. Wang, "A survey on social manufacturing: A paradigm shift for smart prosumers," *IEEE Trans. Comput. Social Syst.*, vol. 10, no. 5, pp. 2504–2522, Oct. 2023.

[11] L. Ramli, Z. Mohamed, A. M. Abdullahi, H. I. Jaafar, and I. M. Lazim, "Control strategies for crane systems: A comprehensive review," *Mech. Syst. Signal Process.*, vol. 95, pp. 1–23, Oct. 2017.

[12] S. Tariq, M. Hussein, R. D. Wang, and T. Zayed, "Trends and developments of on-site crane layout planning 1983–2020: Bibliometric, scientometric and qualitative analyses," *Construction Innov.*, vol. 22, no. 4, pp. 1011–1035, 2022.

[13] T. S. Tamir et al., "Machine-learning-based monitoring and optimization of processing parameters in 3D printing," *Int. J. Comput. Integr. Manuf.*, vol. 36, no. 9, pp. 1362–1378, 2023.

[14] T. S. Tamir, G. Xiong, Q. Fang, X. Dong, Z. Shen, and F.-Y. Wang, "A feedback-based print quality improving strategy for FDM 3D printing: an optimal design approach," *Int. J. Adv. Manuf. Technol.*, vol. 120, no. 3, pp. 2777–2791, 2022.

[15] T. S. Tamir et al., "Design and optimization of a control framework for robot assisted additive manufacturing based on the Stewart platform," *Int. J. Control, Automat. Syst.*, vol. 20, no. 3, pp. 968–982, 2022.

[16] A. Valencia, R. Mugge, J. Schoormans, and H. Schifferstein, "The design of smart product-service systems (PSSs): An exploration of design characteristics," *Int. J. Des.*, vol. 9, no. 1, pp. 13–28, 2015.

[17] M. Fargnoli and N. Haber, "A QFD-based approach for the development of smart product-service systems," *Eng. Rep.*, vol. 5, no. 11, 2023, Art. no. e12665.

[18] Y. Chang, X. Ming, X. Liao, Y. Bao, Z. Chen, and W. Song, "Sustainable value creation through customization for smart PSS models: A multi-industry case study," *J. Manuf. Technol. Manage.*, vol. 35, no. 1, pp. 29–53, 2024.

[19] H. B. John, "Future challenges for loader crane manufacturers," *International Cranes and Specialized Transport*. Accessed: Jun. 13, 2022. [Online]. Available: https://www.cranebriefing.com/news/future-challenges-for-loader-crane-manufacturers/8020629.article

[20] Nowswing. Accessed: Oct. 30, 2023. [Online]. Available: https://www.noswing.fi/

[21] "Smart features." Konecranes. Accessed: Sep. 10, 2023. [Online]. Available: https://www.konecranes.com//sites/default/files/2022-03/Smart

[22] "IOT—Heavy material vehicle monitoring." VerveTronics. Accessed: Sep. 25, 2023. [Online]. Available: https://www.vervetronics.com/solutions/iot-heavy-material-vehicle-monitoring/

[23] G.-Y. Xiong, P. Helo, S. Ekstrom, and T. S. Tamir, "A case study in social manufacturing: From social manufacturing to social value chain," *Machines*, vol. 10, no. 11, 2022, Art. no. 978.

[24] G. W. Shepherd, R. J. Kahler, and J. Cross, "Crane fatalities—A taxonomic analysis," *Saf. Sci.*, vol. 36, no. 2, pp. 83–93, 2000.

[25] W.-c. Shin, H.-W. Yeo, J.-h. Kwon, and K.-H. Yi, "A study on cause analyses of fatal injuries by the mobile cranes," *J. Korea Saf. Manage. Sci.*, vol. 18, no. 1, pp. 9–15, 2016.

[26] W. Zhou, T. Zhao, W. Liu, and J. Tang, "Tower crane safety on construction sites: A complex sociotechnical system perspective," *Saf. Sci.*, vol. 109, pp. 95–108, Nov. 2018.

[27] S. Sadeghi, N. Soltanmohammadlou, and P. Rahnamayiezekavat, "A systematic review of scholarly works addressing crane safety requirements," *Saf. Sci.*, vol. 133, 2021, Art. no. 105002.

[28] J. Lee, I. Phillips, and Z. Lynch, "Causes and prevention of mobile crane-related accidents in South Korea," *Int. J. Occupat. Saf. Ergonom.*, vol. 28, no. 1, pp. 469–478, 2022.

[29] C. Kan, P. Zhang, Y. Fang, C. Anumba, and J. Messner, "A taxonomic analysis of mobile crane fatalities for CPS-based simulation," in *Proc. 17th Int. Conf. Comput. Civil Building Eng.*, 2018, pp. 1–8.

[30] B.-J. Yoon, K.-S. Lee, and J.-H. Lee, "Study on overturn proof monitoring system of mobile crane," *Appl. Sci.*, vol. 11, no. 15, 2021, Art. no. 6819.

[31] F. Omar, F. Karray, O. Basir, and L. Yu, "Autonomous overhead crane system using a fuzzy logic controller," *J. Vib. Control*, vol. 10, no. 9, pp. 1255–1270, 2004.

[32] Y. Kawasaki, A. Kaneshige, and S. Ueki, "Development of the autonomous mobile overhead traveling crane in consideration of on-line obstacle recognition, path planning and oscillating control," in *Proc. 11th Int. Conf. Inform. Control, Automat. Robot. (ICINCO)*, vol. 2, Piscataway, NJ, USA: IEEE Press, 2014, pp. 382–389.

[33] Z. Chen and W. Meng, "Research and prospect of intelligent crane system," *Chin. J. Construction Machinery*, vol. 42, pp. 39–43, 2011.

[34] J. Smoczek, J. Szpytko, and P. Hyla, "The application of an intelligent crane control system," *IFAC Proc. Vol.*, vol. 45, no. 24, pp. 280–285, 2012.

[35] H. D. Zhao, H. Z. Wang, G. N. Liu, C. Li, and M. H. Zhao, "The application of Internet of Things (IOT) technology in the safety monitoring system for hoisting machines," *Appl. Mech. Mater.*, vol. 209, pp. 2142–2145, Oct. 2012.

[36] D. Zhong, H. Lv, J. Han, and Q. Wei, "A practical application combining wireless sensor networks and Internet of Things: Safety management system for tower crane groups," *Sensors*, vol. 14, no. 8, pp. 13794–13814, 2014.

[37] C. Zhou, H. Luo, W. Fang, R. Wei, and L. Ding, "Cyber-physical-system-based safety monitoring for blind hoisting with the Internet of Things: A case study," *Automat. Construction*, vol. 97, pp. 138–150, Jan. 2019.

[38] H. Wu, B. Zhong, H. Li, H.-L. Chi, and Y. Wang, "On-site safety inspection of tower cranes: A blockchain-enabled conceptual framework," *Saf. Sci.*, vol. 153, 2022, Art. no. 105815.

[39] J. Olearczyk, Z. Lei, B. Ofrim, S. Han, and M. Al-Hussein, "Intelligent crane management algorithm for construction operation," *Proc. 32nd Int. Symp. Automat. Robot. Construction (ISARC)*, Oulu, Finland, 2015, pp. 15–18.

[40] X. Ma and H. Bao, "An anti-swing closed-loop control strategy for overhead cranes," *Appl. Sci.*, vol. 8, no. 9, 2018, Art. no. 1463.

[41] N. Sun and Y. Fang, "Bounded tracking and anti-swing control of underactuated cranes for payload transportation and lowering," in *Proc. 32nd Chin. Control Conf.*, Piscataway, NJ, USA: IEEE Press, 2013, pp. 653–660.

[42] J. Smoczek and J. Szpytko, "Particle swarm optimization-based multivariable generalized predictive control for an overhead crane," *IEEE/ASME Trans. Mechatron.*, vol. 22, no. 1, pp. 258–268, Feb. 2017.

[43] M. J. Maghsoudi, Z. Mohamed, S. Sudin, S. Buyamin, H. Jaafar, and S. Ahmad, "An improved input shaping design for an efficient sway control of a nonlinear 3D overhead crane with friction," *Mech. Syst. Signal Process.*, vol. 92, pp. 364–378, Aug. 2017.

[44] B. Rong, X. Rui, L. Tao, and G. Wang, "Dynamics analysis and fuzzy anti-swing control design of overhead crane system based on Riccati discrete time transfer matrix method," *Multibody Syst. Dyn.*, vol. 43, pp. 279–295, Oct. 2018.

[45] S. Han, S. Hasan, A. Bouferguene, M. Al-Hussein, and J. Kosa, "An integrated decision support model for selecting the most feasible crane at heavy construction sites," *Automat. Construction*, vol. 87, pp. 188–200, Mar. 2018.

[46] J. K. Ray, A. Singh, Q. M. Alfred, S. Shome, and R. Bera, "5G URLLC communication system with cognitive radio and frequency diversity reception for improving reliability in smart factory e-cranes operation," in *Proc. IEEE MTT-S Int. Microw. RF Conf. (IMARC)*, Piscataway, NJ, USA: IEEE Press, 2019, pp. 1–5.

[47] J. Autiosalo, R. Ala-Laurinaho, J. Mattila, M. Valtonen, V. Peltoranta, and K. Tammi, "Towards integrated digital twins for industrial products: Case study on an overhead crane," *Appl. Sci.*, vol. 11, no. 2, 2021, Art. no. 683.

[48] C. Huang, W. Li, W. Lu, F. Xue, M. Liu, and Z. Liu, "Optimization of multiple-crane service schedules in overlapping areas through consideration of transportation efficiency and operational safety," *Automat. Construction*, vol. 127, 2021, Art. no. 103716.

[49] M. Burkhardt and O. Sawodny, "A graph-based path planning algorithm for the control of tower cranes," in *Proc. Amer. Control Conf. (ACC)*, Piscataway, NJ, USA: IEEE Press, 2021, pp. 1736–1741.

[50] Y. Zhao, C. Cao, and Z. Liu, "A framework for prefabricated component hoisting management systems based on digital twin technology," *Buildings*, vol. 12, no. 3, 2022, Art. no. 276.

[51] P. M. Williams, "Techniques for root cause analysis," *Baylor Univ. Medical Center Proc.*, vol. 14, no. 2, 2001, Art. no. 154.

[52] J. Liu, P. Jiang, and J. Leng, "A framework of credit assurance mechanism for manufacturing services under social manufacturing context," in *Proc. 13th IEEE Conf. Automat. Sci. Eng. (CASE)*, Piscataway, NJ, USA: IEEE Press, 2017, pp. 36–40.

[53] "Insight ningbo." Accessed: Jul. 15, 2023. [Online]. Available: http://news.cnnb.com.cn/system/2022/01/19/030322900.shtml

[54] "Daily ningbo, China. Promotion on the modernization of management and governance for construction business." Accessed: Jul. 30, 2023. [Online]. Available: http://daily.cnnb.com.cn/nbrb/html/2022-01/21/content_1305563.htm

[55] F.-Y. Wang, X. Shang, R. Qin, G. Xiong, and T. R. Nyberg, "Social manufacturing: A paradigm shift for smart prosumers in the era of societies 5.0," *IEEE Trans. Comput. Social Syst.*, vol. 6, no. 5, pp. 822–829, Oct. 2019.

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