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Pay-Per-Sustainable-Use: A Case of Product Service System Innovation

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Abstract

Shifting to product-service systems (PSS) enables pay-per-use revenue models to positively impact social, economic, and environmental interests. However, few studies have shown how user-oriented PSS offers can be adopted in traditional sectors of the economy. This paper introduces the concept of "pay-per-sustainable-use" in construction: PSS adoption that promotes conscientious equipment use and long-term value for its stakeholders. A design science research project was conducted in a supplier of construction tower cranes aiming to redesign their product portfolio. This project shows how information systems can modernize business models toward smarter machinery for sustainable construction. For theory, we characterize the pay-per-sustainable-use revenue model using PSS. For practice, we present a pioneer case of PSS design in construction tower cranes and suggest accessible guidelines to assist construction equipment managers in selecting the best digital transformation strategy that protects people, machines, and the building environment.

Keywords: Pay-per-use, product service system, construction, smart crane

Introduction

The blend of physical and digital materialities can generate product offers with sustainable value and innovative business models (Novales et al. 2016; Yoo et al. 2012; Zheng et al. 2019). These new products are "smarter" and connected using digital technologies such as cloud, internet of things (IoT), mobile, or big data infrastructures (Porter and Heppelmann 2015), raising new questions for managers about the competitiveness of existing portfolios and the definition of a digitalization strategy (Karttunen et al. 2021; Mohelska and Sokolova 2016; Novales et al. 2016). Theoretical approaches have been proposed to innovate business models combining servitization and digital technologies; however, "*further empirical research is still needed to validate the elements*" (Frank et al. 2019).

Product-service systems (PSS) are integrated packages of products (tangible) and services (intangible) to deliver the customers' needs while enhancing both competitiveness and sustainability (Tukker 2004). The organizational impact of PSS can be significant. However, the conversion from pure physical products to a PSS market enhanced by advanced information technologies is challenging. For example, the changes in product ownership and use, instant interaction with the customer, and company focus (Frank et al. 2019; Gaiardelli et al. 2014). To be sustainable, a PSS must have characteristics and produce actions that contribute to building a better future for the organizations and society (Funk 2004).

Pay-per-use is one of the possible revenue models for PSS (Gaiardelli et al. 2014; Tukker 2004) characterized by the payment of service units instead of owning the product, with promising results for sustainability (Bocken et al. 2018). The internet of things is one of the major drivers for the emergence of this model in physical products. However, pay-per-use may also increase the company's uncertainty about revenues, demanding a detailed analysis of the expected use and the combination of services available (Sato and Nakashima 2019). There are many options ranging from pure physical products to pure digital services. Therefore, additional research on PSS-enabled business models will be necessary (Waidelich et al. 2019).

This paper presents the results of a research project aiming to develop PSS for sustainable construction in a traditional supplier of construction cranes. Construction cranes are basically physical structures to lift and move suspended loads at the construction site. They can be static (e.g., tower cranes) or mobile (usually mounted on tires or mobile structures like trucks). The case company operates in a sector of the economy that is particularly affected by three safety culture responsibilities: professional, social, and environmental (Rajanen and Rajanen 2019). Our intervention reveals (1) an opportunity to change the revenue model by adopting PSS, (2) the potential to improve human safety in construction sites, (3) the possibility to reduce operational costs, and (4) differentiation of the company offer in a sector of the economy that is well adapted to temporary use of their equipment (e.g., renting cranes for particular periods), but still far from putting sustainability on the top of construction equipment priorities, struggling with the problems of traditional strategies (Niu et al. 2019). IT-enabled sustainable construction cranes are the primary goal of our case company.

The remainder of this paper is organized as follows. The next section introduces the study motivation, the research context, and the main steps of our design science research (Peffers et al. 2007; Venable et al. 2016). The following section revises key literature about sustainability in the construction industry, digital potential for traditional construction cranes, and PSSs. The artifact design and development are subsequently detailed, and the evaluation of a PSS prototype is presented according to the guidelines provided by Venable et al. (2016). Next, the findings are discussed, and the paper closes by stating the leading conclusions, study limitations, and opportunities for future work.

Motivation and Research Approach

This research was launched after contacting a construction crane supplier with direct sales and equipment renting possibilities. They were preparing a research and development (R&D) project to improve the safety and performance of their equipment using digital technologies. The three critical motives for their interest in improving crane business included (1) the steady increase in maintenance costs, (2) the interest in quality certification requiring compliance to multiple standards (e.g., EN 14439; OSHA CPL 02-01-057: Compliance Directive for the Cranes and Derricks in Construction Standard), and (3) the recent hazards with cranes due to human causes (e.g., poor operation procedures, inadequate qualification of the operator, deficient alert systems, and insufficient measures to prevent unauthorized access) but also adverse weather conditions (e.g., wind), which are expected to be more frequent due to climate changes.

The case company integrates a major construction group with a background in occupational health and safety, training, and construction safety audits. The managers wanted to differentiate their market offer and create new services for customers. The R&D project was concluded at the end of 2021: design small-scale prototypes to understand the opportunities of Industry 4.0 (Oesterreich and Teuteberg 2016) with its multiple technologies, for example, IoT, cloud, mobile, or RFID (radio frequency identification).

The need to design an artifact embedding different technologies in a complex sociotechnical context seemed to be a perfect match for design science research (DSR) (Hevner et al. 2004; Peffers et al. 2007). The DSR approach needs to balance artifact development with theoretical contributions (Baskerville et al. 2018). On the one hand, Industry 4.0 technology is changing how business operates. It is capable of generating a new vision for an artifact that "*provides fundamental mechanisms by which people communicate and interact* (...) *and systematically protects the environment and enhances sustainability through ecological efficiency, equity, and effectiveness*" (Baskerville et al. 2018). On the other hand, the theoretical impact for sustainability with digital transformation, usually incorporated in the artifact, is in our case aiming at technology and science evolutions supported by rigorous domain knowledge bases (Baskerville et al. 2018).

We selected the steps proposed by Peffers et al. (2007) for DSR projects, namely, (1) identification of the problem and study motivation, (2) establishing objectives for the solution, (3) design and development, (4) demonstration, (5) evaluation - as detailed in Venable et al. (2016), and (6) communication. Complementarily, we followed the guidelines suggested by Gregor and Hevner (2013) to publish DSR results (DSR step 6), classified as a Level 2 contribution type for nascent design theory producing knowledge for an operational architecture (Gregor and Hevner 2013).

Figure 1 summarizes the six main steps (Peffers et al., 2007) of our DSR.

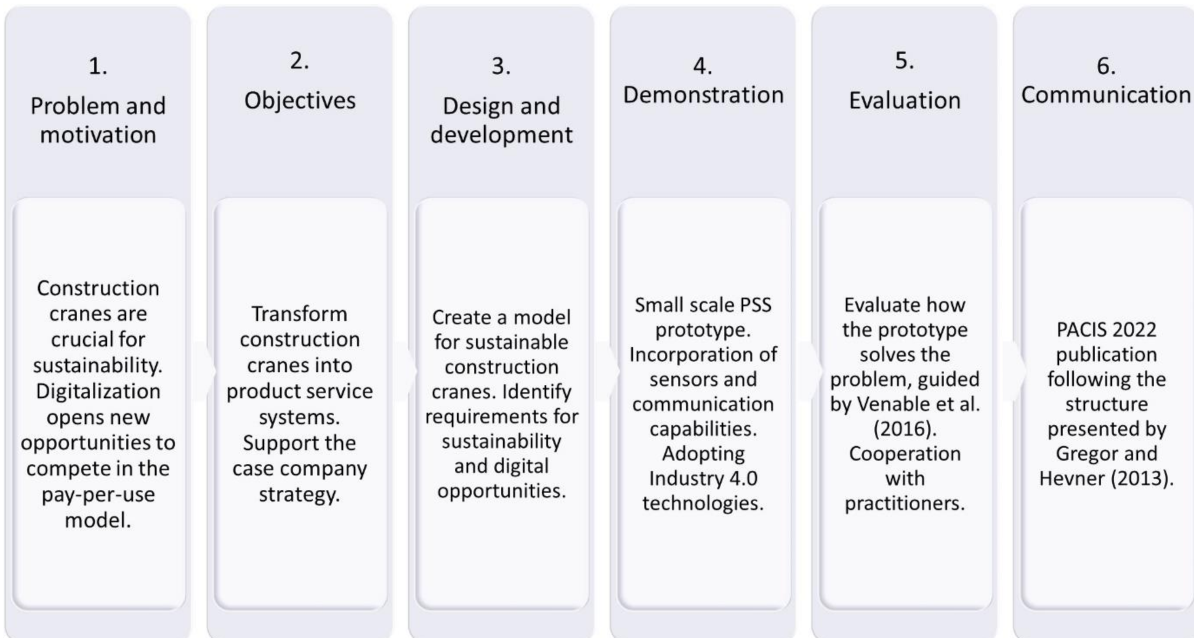

Figure 1. DSR Presentation

Having stated the purpose, the class of problems, and the relevance of our study in the organizational setting (DSR step 1), the subsequent section revises literature "*that is relevant to the study, including theories, empirical research studies and findings/reports from practice*" (Gregor and Hevner 2013).

The literature review allowed us to clarify the objectives for the solution (DSR step 2) and prepare the foundations for design and development.

Literature Review

This section starts with the interpretation of sustainable construction and its relationship with equipment. Subsequently is explained how construction cranes can contribute to the challenge of sustainability. The following section introduces the stage of digital transformation in tower/mobile cranes and identifies enabling technologies. Finally, the PSS paradigm is defined.

Disentangling Sustainable Construction

Sustainable information systems should aim at the most relevant challenges of the target economic sector. Therefore, we conducted a preliminary search in Web of Science (WoS) to identify related concepts for sustainable construction and evaluated the results with VOSViewer (van Eck and Waltman 2010) for the 92 papers in the list (all fields, no time restriction).

The keywords merged "sustainable construction" and "equipment" – the latter was selected because we could not find results focusing specifically on construction cranes (last updated 13/03/2022), and the results (co-occurrence, all keywords) are presented in Figure 2.

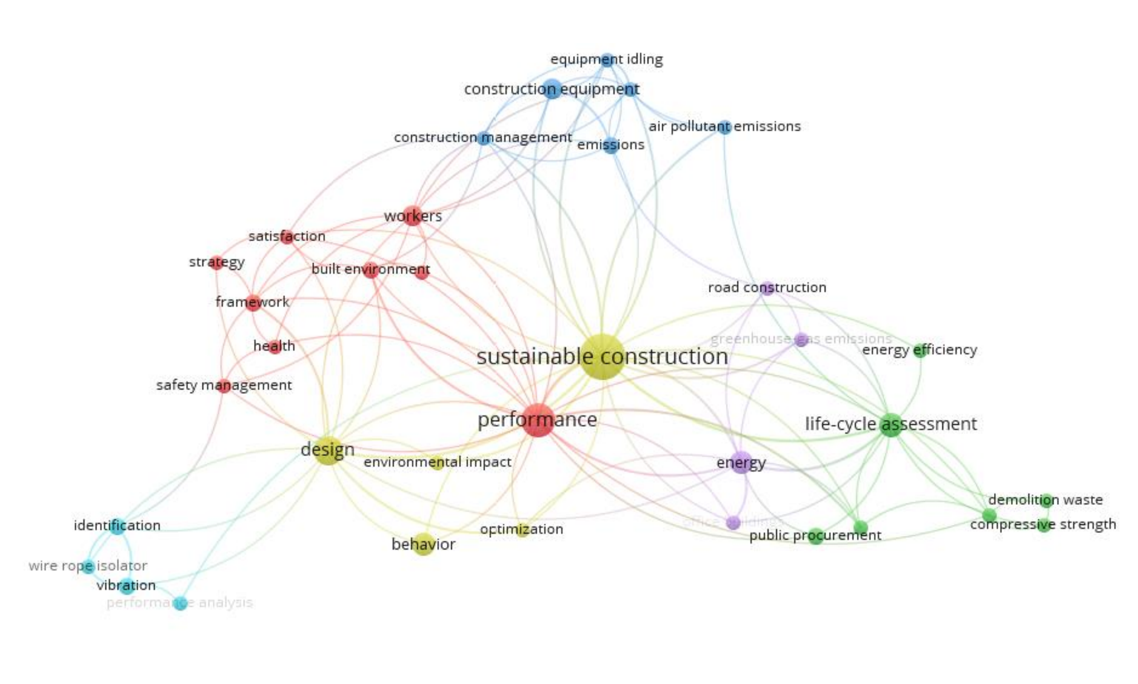

Figure 2. Sustainable Construction and Equipment Suppliers – Key Concepts

Multiple concepts and clusters (one for each color) can be identified in Figure 2, including operation conditions (e.g., equipment idling in the blue cluster on the top), energy efficiency and emissions (green cluster on the right), but also the workers' conditions (red cluster) and economic performance (yellow cluster). It becomes clear that sustainable construction information systems integrate three key elements: social, economic, and environmental (Sev 2009); curiously, a Google Scholar Search using the keyword combination "sustainable tower crane" OR "sustainable construction crane" OR "sustainable mobile crane" returns 0 results. Moreover, the network reveals that most nodes are similar in size and are dispersed in different clusters (ranging from safety management to energy efficiency), suggesting an opportunity for their integration into construction equipment. Comprehensive approaches for information systems development aiming at the sustainability of this crucial equipment are still immature. However, significant contributions have been done to specific aspects of construction cranes' sustainability (e.g., human protection or environmental impacts), with the potential to be integrated, as presented in the following section.

The Possible Role of Construction Cranes for Sustainable Construction

The construction sector points to high rates of accidents compared to other industries (Gibb et al. 2014; Mohandes et al. 2022). The workplace is one of the most critical locations for accidents, containing several possible causes such as the workers' behavior, conditions (e.g., equipment), layout, or communication issues (Gibb et al. 2014; Mohandes et al. 2022). Crane operations can cause severe injuries, for example, in the case of collisions, adverse weather conditions, fatigue of operator, overriding of limiters, inattention, or even mobile phone use during operation (Lee et al. 2012; Loughborough and UMIST 2003; Niu et al. 2019; Raviv et al. 2017; Zhong et al. 2014). Nevertheless, technical failures are hazardous situations requiring constant surveillance, emphasizing adequate equipment maintenance (Lingard et al. 2021; Raviv et al. 2017).

Some studies have also addressed the environmental aspects, such as the consumption of resources in tower cranes. Hasan et al. (2013) presented a methodology to evaluate the carbon footprint of the equipment, comparing the use of traditional and double-jib tower cranes for improved performance. Remarkably, tower cranes can reach up to 21% of energy consumption in high-rise buildings, the highest percentage among all the machines, engines, and equipment (Korol and Korol 2018). Smart technologies can monitor and improve environmental conditions in this demanding context (Xu et al. 2022).

Safety, environment, and other factors can affect the economic sustainability of tower cranes. For example, selecting the best location on the site to reduce rent and operation costs (Moussavi Nadoushani et al. 2017). Moreover, the long useful life of the tower crane facilitates the return of investments in automation, as demonstrated in the study presented by Rosenfeld and Shapira (1998), for example, in the case of improved operating conditions. A summary of the role of construction cranes in the sustainable construction industry is included in Table 1.

Sustainability	Sustainable Construction Cranes (SCC)	References
Social	SCC1 - Protect the operator in crane operation (e.g., alarms for dangerous operations) SCC2 - Protect other workers at the construction site SCC3 - Minimize risks for persons surrounding the site SCC4 - Ensure traceability in case of an accident	(Fang et al. 2016; Loughborough and UMIST 2003; Mohandes et al. 2022; Niu et al. 2019; Raviv et al. 2017; Xu et al. 2022)
Economic	SCC5 - Avoid damages in adjacent structures (e.g., collision) SCC6 - Select the best location at the construction site SCC7 - Protect the crane structure SCC8 - Increase performance with appropriate maintenance procedures	(Jiang et al. 2022; Lee et al. 2012; Zheng et al. 2013; Zhong et al. 2014)
Environmental	SCC9 - Minimize energy consumption during crane operation SCC10 - Reduce energy in crane movement (in the case of mobile cranes and tower crane transportation between sites) or maintenance (both types of cranes) SCC11 - Minimize CO^2 emissions	(Hasan et al. 2013; Korol and Korol 2018; Xu et al. 2022)

Table 1. Elements of Sustainable Construction Cranes

Table 1 exposes opportunities to improve sustainability using construction cranes. The three elements are interrelated. For example, economic outcomes can be a consequence of social (e.g., accident reduction) and environmental (e.g., fewer resources used) actions. The next section discusses how technology can be used to address them.

Enablers for Digital Transformation in Sustainable Construction Cranes

The past two decades brought multiple advances in construction crane digitalization. The study presented by X. J. Zheng et al. (2013) presents a control system for multiple tower cranes using RFID. The authors highlight three main benefits of the proposed solution: collision prevention, increased efficiency, and traceability in case of accidents. Data recording is one of the functions of the system presented in Wang et al. (2007), complementing with anti-sway automatic operation and threshold supervision, for example, for efficiency: "*when lifting moment is over half of the rating value, the moment limitator will cut down tower crane to the second highest speed*" (Wang et al. 2007) or safety (e.g., show a warning if "*hoisting moment is up to 90% of the rating value*" (Wang et al. 2007).

Other studies focus on crane operator support, such as a navigation system for blind lifts (Lee et al. 2012) or protecting workers from unsafe moving objects via GPS (global positioning system) and instant warning systems (He 2018). The literature is rich in examples that try to protect different stakeholders of the construction crane, for example, building contractors (privileging efficiency), inspectors (seeking traceability), equipment operators, and their colleagues at the construction site. However, there is a lack of studies that address the protection of crane access (e.g., non-skilled or non-authorized personnel in the cabin) and the opportunities for predictive maintenance. Moreover, we could not find studies aiming at the case of rented cranes - the equipment owner is not constantly at the building construction site. This scenario is relevant for our company and its sustainability strategy because there are risks of careless use (motivated by not owning the product) leading to reduced life or other problematic consequences (Tukker 2004).

More recently, the lab test introduced by Niu et al. (2019) aiming at tower crane safety reminds us that "*construction remains one of the most dangerous sectors, warranting more innovative or even revolutionary approaches*". The authors implemented a combination of GPS (to calculate the distance of trolley), accelerometer (slewing angle of jib), magnetometer (height of hook), barometers (heading angle of the beam), and gyroscope (beam motions) to support automatic response to dangerous conditions (Niu et al. 2019). The emergence of smart construction sites may adopt different technologies. The work of Xu et al. (2022) presents several examples of artificial intelligence, automation, enhanced visualization, network, and IoT. Safety and maintenance are deeply interrelated (Zhou et al. 2018).

Table 2 presents relevant digital opportunities found in the literature to improve tower/mobile crane sustainability according to social, economic, and environmental impacts.

Sustainability	**Digital Opportunities (DO)**	**References**
Social	DO1 - IoT for sensing dangerous conditions or limits that must be ensured (addresses SCC1-3 identified in Table 1) DO2 - RFID to identify authorized users (e.g., trained personnel*) or personal protective equipment use (SCC1) DO3 - Sensors that detect dangerous positions of the crane and load accidents (SCC1- SCC3) DO4 - Information technologies for "black box" can improve compliance (SCC4) DO5 - Blockchain technology to ensure immutable data (**) (SCC4)	(Lee et al. 2012; Teizer 2015; Wang et al. 2007; Xu et al. 2022; Zheng et al. 2013)
Economic	DO6 - Collision detection systems (SCC5) DO7 - GPS to identify the correct location of the crane in installation and construction site changes* (SCC6) DO8 - Movement sensors to protect the crane during off-duty periods* (SCC7) DO9 - Preventive maintenance algorithms (SCC8) DO10 - Monitoring crane use with IoT to predict maintenance periods* (SCC8) DO11 - Optimize crane movement in different sites with intelligent algorithms. It is related to the concept of fleet optimization (a group of similar equipment that can share data), not previously identified in the literature (SCC10)*	(He 2018; Niu et al. 2019)
Environmental	DO12 - More efficient electrical or mechanical parts (SCC9) DO13 - Location of the crane to minimize operation movements (SCC10)	(Hasan et al. 2013; Sev 2009; Xu et al. 2022)

Sustainability	Digital Opportunities (DO)	References
	DO14 - Adequate maintenance procedures supported by real-time monitoring to reduce wastes* (SCC11) DO15 - Minimize supplier travel to evaluate the crane in each site using remote sensing* (SCC10-SCC11)	

Table 2. Digital Opportunities for Sustainable Construction Cranes

Legend: (*) own suggestion; (**) as an extension to the work presented by Wang et al. (2007)

Information systems are essential to deploy the three elements of sustainability in the leftmost column. However, most of the references found in the literature detail specific applications (e.g., sensors for collision detection), lacking an integrated model to guide crane suppliers in digital transformation for sustainability, and compelling business cases to inspire this industry. The following section explores the integration of physical products and immaterial services to improve the offer value (Reim et al. 2015).

Product-Service Systems: Blending Physical and Digital Materialities

The fourth industrial revolution and the trend for servitization are blurring the frontiers between digital and physical elements (Novales et al. 2016; Porter and Heppelmann 2015; Yoo 2010). The opportunities to create increasingly digitized and smart products are a priority for managers (Porter and Heppelmann 2015). There are three core elements to consider, namely, the physical parts (e.g., tower crane mechanics), the smart components (e.g., sensors, microprocessors), and the connectivity layer that ensures communication between the product and the cloud (Porter and Heppelmann 2015). The new layered architecture described by Yoo et al. (2010) can improve the market offering with value-added services to the end-user.

PSSs emerged as a particular form of market offer that puts sustainability and societal virtues as a priority, requiring that "*product developer must become more aware of complex life cycle issues, multiple (and increased variance of) stakeholders, multiple product lives, societal issues, liability (…)*" (McAloone and Andreasen 2004). The definition of PSS is closely related to sustainability, digital developments, and innovative business models (Pan et al. 2019). Servitization involving social and material aspects opens new opportunities for the circular economy, such as creating product biographies (Spring and Araujo 2017) that record all the possible trajectories of products (e.g., transformations in its structure, different users over time). As stated by Tukker (2004), PSSs have the extraordinary potential to simultaneously improve competitiveness and sustainability.

The service delivered to building contractors is usually complemented with crane maintenance plans, especially when renting is the revenue model. PSSs have already been implemented in construction crane suppliers, as explained by Ostaeyen and Duflou (2010) for a major Belgium crane producer that changed its revenue model from selling to crane rental. However, Ostaeyen and Duflou's (2010) work does not explore information systems or sustainability in its social, economic, and environmental aspects. Moreover, among the different capabilities of IoT-enabled PSS business models recently presented by Karttunen et al. (2021), we could not find details for long-term sustainable models in critical construction equipment.

The design of a PSS that explores how tower cranes are used with a long-term perspective is promising. Its design must follow a sequence of steps that start with the project preparation and analysis of customer requirements, idea generation, selection, design, prototype, implementation, and evaluation (Clayton et al. 2012). These steps align well with our DSR approach, as described in the next section.

Towards Sustainable Construction Cranes

This section reveals how a 100% physical tower crane product can be transformed into a PSS supported by information technologies in a complex sociotechnical context of operation.

Artifact Description

The system design and development (DSR step 3) were conducted after the initial literature review (that proceeded during the entire project) and contacts with experts in construction safety.

We named the revenue model enabled by the proposed solution as *pay-per-sustainable-use*. This solution balances maintenance reduction costs (their benefit) and the risk of decreasing revenues in low usage scenarios (if the equipment is less used, the customer necessarily pays less). On the one hand, equipment efficiency and minor damage by collision or improper operation can positively impact their costs. On the other hand, the building contractor may be willing to pay a little more if the equipment also protects them in case of hazards and confirms the commitment of all the parties to sustainable construction. Figure 3 presents the proposed architecture using ArchiMate language (The Open Group 2019).

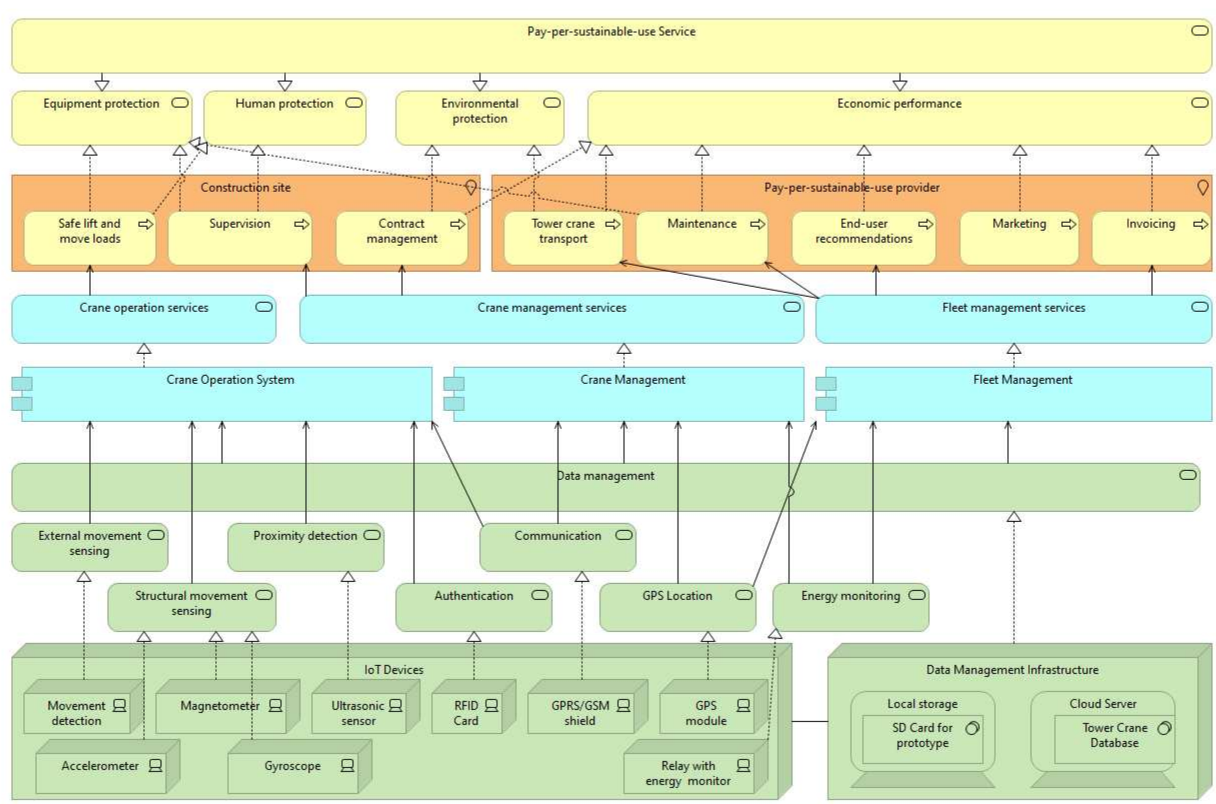

Figure 3. The Pay-Per-Sustainable-Use Architecture in Construction Cranes

ArchiMate is increasingly used to formalize complex systems, like in the work of Tchoffa et al. (2021), for interoperability in IoT contexts. Figure 3 presents three layers of the architecture, namely, the technology infrastructure (green), the applications (blue), and the business layer using processes (arrow icon), locations (orange), and the services deployed (at the top, oval icon) with the PSS. ArchiMate adopts a service-oriented modeling approach – a layer provides a service (elements with the oval icon) to the upper layers. Integrating social, economic, and environmental sustainability requires that multiple construction processes have real-time monitoring and applications tailored to each stakeholder (crane operator, contractor, construction crane owner operating the fleet). Payment indexed to sustainability outcomes requires a combination of multiple IoT devices (on the bottom-left) and data analytics, subsequently detailed. The model for the sensing and communication layer of the PSS (Miranda et al. 2017; Porter and Heppelmann 2015) is presented in Figure 4.

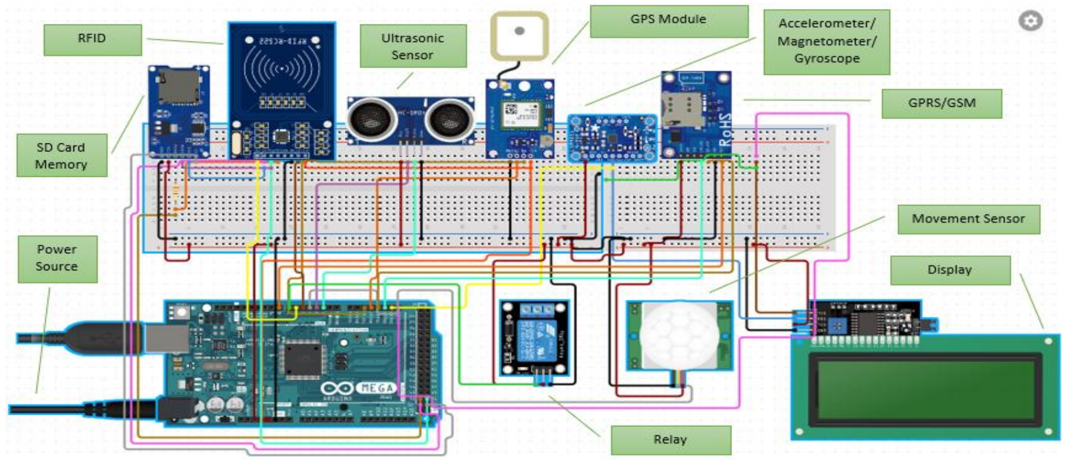

Figure 4. Integrated Model with Sensors, Actuators, and Communication

Figure 4 identifies small-scale sensor technologies (e.g., ultrasonic, movement sensor) and communication and location technologies (e.g., GPRS/GSM/GPS). Moreover, there are specific interfaces for assessing a mobile tool and presenting alerts to operators (relay to control external equipment and connection with a microcontroller on the bottom left). This step helped identify opportunities for sustainability. For example, an operator interface to provide instant warnings - represented by the display on the bottom-right, recording events in a blockchain infrastructure. The current prototype uses an SD card for local updates of the PSS log, including alarms relevant to insurance inspections.

Figure 5. Tower Crane and Prototype for Sustainability

Figure 5 portrays a tower crane of the case company (on the left) and the developed prototype (rightmost image) to support the demonstration (DSR step 4). The model obtained at the design stage uses an Arduino Mega microprocessor and different sensors and communication elements. The tests executed with the low-cost prototype (cost below 300€) supported our discussion about the opportunities for transformation of the equipment using information systems. Afterward, the prototype specifications assisted in examining industrial-scale equipment suitable for construction. As found in the literature review phase, current prototypes for sustainable tower cranes are evolving but do not yet consider the needs of all the tower crane stakeholders. Two complementary tools, namely, an anemometer for wind monitoring and surveillance cameras (e.g., for operation assistance and protection of the facility), are not included in this version of the prototype because their functionalities are straightforward, and it is preferable to buy the real-scale models (standard in the market) directly.

The following section presents the joint evaluation (step 5 of the DSR) made by researchers and practitioners.

Evaluation

This section is guided by the four steps suggested by the FEDS framework for the evaluation of DSR, namely, "*(1) explicate the goals of the evaluation, (2) choose the evaluation strategy or strategies, (3) determine the properties to evaluate, and (4) design the individual evaluation episode(s)*" (Venable et al. 2016).

The model for an innovative PSS with value-added sustainability is the main result expected by our case company. Therefore, the evaluation episode involved an instantiation of the artifact and its potential to change sociotechnical characteristics of the construction environment. Social characteristics included the potential of data to avoid accidents, the increase in equipment performance, and the expanded business offer of the company. The technical aspects comprised the physical layers of the PSS and the digital affordances of the resulting artifact for interaction and data processing.

Among the four possible strategies presented by Venable et al. (2016), a single evaluation episode for the artifact assessment and "*human risk and effectiveness*" for the social changes involved in the setting are the most related. In this case, supported by field observation, document collection, and interviews with the company experts and consultants from their group. After conducting a market search, the components did not reveal technological challenges. There are sensors and actuators available to create the solution presented in our model, and the software development tasks use well-known frameworks. For that reason, the feasibility of the artifact was checked in a single episode with "*small and simple construction of design, with low social and technical risk and uncertainty*" (Venable et al. 2016). However, the impact on the organizational setting and the people involved can be significant.

The artifacts created in our research (models and prototype instantiation) were evaluated after the design phase, addressing the improvements achieved with the PSS to the case company strategy and operation. Similar to the example presented in Venable et al. (2016) for a summative evaluation, it was interpretive and included researchers, elements from the IT team, and construction experts. The prototype was also casually demonstrated (brief presentations during commercial visits) to customers of the organization. Regarding the prototype instantiation, the conclusions are positive and allow identifying the most relevant use cases for a sustainable construction crane.

Table 3 highlights the most relevant goal to the company, the enabling technologies, and use cases for each sustainability element.

Sustainability	**Goal**	**Technology**	**Use Cases for Sustainable IS**
Social	Compliance	SD Card, GPRS/GSM Shield, GPS, Blockchain	Information stored at the SD card (Black Box implementation) Proof of notification in case of limit violations

Sustainability	Goal	Technology	Use Cases for Sustainable IS
			Confirmation of the crane location for A) correct contract execution; B) In case of hazard investigation Movement sensor off-the-job activate security camera in the cabin
	Authorized operation	RFID	Identify the crane operator Identify if the crane operator uses personal protective equipment Record operator experience in tower cranes (issue certificate at contract completion)
	Safety alerts	Ultrasonic sensor (other types can be used), magnetometer, gyroscope, Smartwatch (option for instant warning)	Activate crane safety systems (e.g., emergency stop) Alert the crane operator Alert the safety officer
Economic	Hours of operation	Encoder	Equipment idle monitoring
	Responsible use	Encoder, Ultrasonic sensor	Identify careless use during contract execution (collision alert log) Monitor the number of hours to predict maintenance opportunity Obtain a ratio of working hours vs. number of load movements
	Protect equipment from damages	Ultrasonic sensor, magnetometer, gyroscope, RFID	Minimize costs of damaging equipment, ensuring safe operations and alerts Minimize risks of robbery
	Optimize maintenance	Encoder, Bibliographic records, Mobile app, Cloud infrastructure	Algorithm for predictive maintenance based on hours of operation and profile of use
	Contract	Engine block	Blocks crane operation in case of payment failure or irregular operation
Environmental	Energy savings during transport	Encoder, GPS, Decision support algorithms	Energy savings during transport
	Most economic location	GPS, Decision support algorithms	Confirm the location in the best site for the expected load necessities

Table 3. Sustainable Construction Cranes - Prototype

According to the project participants, the vision presented in Table 3 for the three interrelated elements of sustainability can change how the business is conducted nowadays. The first change occurs in the real-time evaluation of contract execution, allowing, for example, to stop the equipment operation in case of problems. Secondly, the system biography (Spring and Araujo 2017) with the chosen parameters can protect the persons involved in the construction site (or nearby) and the supplier's responsibility in case of accidents and unauthorized use of the equipment.

Calibration of measurement equipment will be necessary to ensure trust by the stakeholders, possibly implementing a private blockchain for relevant data in case of hazardous events (e.g., alarms, limits, use/unauthorized use, wind speed). Part of the data, for example, operational data (e.g., hours of operation) required by maintenance algorithms, are not planned to be integrated into the blockchain (redundant sensor measurements can be enough to identify discrepancies and potential problems). Thirdly, while evaluating the system's economic impact, the pay-per-sustainable-use revenue model emerged as a possibility. According to the top manager, this model does not exist in construction cranes, but the proposed IS model allows the required inputs and outputs for its implementation.

The business model includes a fixed and a variable part of the equipment rental price. The fixed part is calculated to protect the equipment immobilization while installed at the customer site. The variable part is charged according to the effective use of loading operations and an agreed contractual penalty for alarm situations that are the client's responsibility. The discussion of the results vis-à-vis the literature findings is presented in the next section.

Discussion

Sustainable construction combines social, economic, and environmental elements of safety culture (Oesterreich and Teuteberg 2016; Rajanen and Rajanen 2019). There is significant overlap among these elements, and it is unquestionable that, in our case, the economic perspective is a determinant of the successful outcome of a PSS. For example, the maintenance improvements allowed by the PSS proposal are the main driver to achieving energy savings and less consumption of resources, motivating the company's investments. We do not consider this effect negative. We argue that IS researchers should seek to balance the organizational benefits and the sustainability goals by creating digitally enabled equipment ecosystems (Ângelo and Barata 2021), particularly in the economic sectors where customers are not yet sufficiently mobilized by holistic sustainability efforts.

Construction cranes are conventional physical assets for occasional use. The mere addition of physical elements is not enough to ensure sustainability goals. For example, proximity sensors to avoid collisions are necessary for safety but challenging to implement if the customer does not value the overhead in the contract. Information systems can change this scenario by extending product value with new services supported by digital technologies. We confirmed that social aspects are challenging for PSS implementation (McAloone and Andreasen 2004) but found the merits of a pay-per-sustainable-use solution that balances the need of all stakeholders.

Some scholars have already analyzed the potential of PSS to reduce environmental impacts (Zheng et al. 2018). However, other authors, for example, Tukker (2004), conclude that "*simple thinking that PSS development will automatically result in an environmental–economic win–win situation also seems to be a myth*" and, as happened in the initial situation of our case company, renting the product may increase risks of improper use and more severe environmental impacts. In fact, Tukker and Tischner (2006) suggest that the sustainability of product services may be higher on "user-oriented services" and "result-oriented services", when contrasted with "product-oriented services". Moreover, there are authors suggesting that dematerialization is frequently associated with modification in ownership structures (Gaiardelli et al. 2014).

The pay-per-use model has already entered the agenda of the construction sector. For example, Fitton et al. (2008) describe a prototype to monitor the use of road patching equipment and calculate billing. The work of Bocken et al. (2018) is one of the more recent inspirational examples of pay-per-use. However, this revenue model supported by real-time monitoring is nascent in construction machinery and difficult without proper IS support. Also, the potential of technologies to deploy smart construction objects is recognized to improve safety in this critical economic sector (Niu et al. 2019). These researchers inspire our study to propose a revenue model for tower cranes in construction that values sustainable use, where payment is user-oriented and result-oriented. Our work adopts a three-fold perspective for sustainability (economic, social, and environmental) in smart construction objects. The artifact produced in our project provides concrete guidelines for creating sustainable tower cranes that promote a safety culture for digital construction (Rajanen and Rajanen 2019), extending the work presented by Karttunen et al. (2021) with the IoT-enabled PSS sustainability capability.

Projectability in design science research provides an exciting lens to evaluate possible world instantiations in different places and times and how the artifact can change reality (Baskerville and Pries-Heje 2019). The first projection is the role of information systems in creating more sustainable use of outsourced equipment. For example, trucks, loaders, or crawlers impact costs, safety, and waste reduction in the construction context. Our findings in the tower crane instantiation offer a starting point to identify the aspects of economic, social, and environmental sustainability that can be improved in a pay-per-sustainable-use model. Transferring a part of the end-user price to savings for suppliers seems more appealing for equipment with high maintenance costs. Two main changes are envisioned for the possible worlds of pay-per-sustainable use. First, increasing awareness of sustainability in the workplace. On the one hand, the supplier may reduce a part of the earnings of sustainable use (increased remaining useful life, reduced wastes, reduced inoperable time), not affecting their profit and differentiating their brand in the market. On the other hand, business contractors protect their human resources and have an additional reason to incorporate sustainable practices in their projects. The steps and lessons learned in our research can be adopted in different use cases. For example, the redesign of safer equipment (e.g., preventing unauthorized use), the increase of useful life (e.g., bike rental), or waste reduction (e.g., intelligent hotel bedrooms with variable prices depending on sustainable use of electricity, water, or other resources according to specific benchmarks).

Conclusions

This paper presents a two-year-long design science research (Peffers et al. 2007; Venable et al. 2016) to create sustainable tower cranes enabled by digital technologies. The findings (1) reveal an IoT-based model for sensing, smart, and sustainable tower crane, (2) a small-scale prototype for its evaluation according to social, economic, and environmental dimensions, and (3) the instantiation of a pay-per-sustainable-use model in a critical-safety traditional sector of the economy.

Our work has several limitations that must be stated. First, although our prototype identified the most relevant parameters, components, and use cases for developing a full-scale implementation of a sustainable tower crane enabled by digital technologies, the research is still at technology readiness level 4. Adopting the model with a selected customer provides a controlled scenario to understand the execution of the pay-per-sustainable-use in practice, namely, the detailed cost-benefit analysis for the lifecycle of the tower crane. For example, maintenance cost evolution, damage report, potential reduction of accidents, customer satisfaction, and increased long-term benefits for the case company. Second, the technologies associated with the fourth industrial revolution are constantly evolving. Other technologies can be used as an alternative to specific sensors or extend the functionalities presented in our instantiation. Third, although the results obtained by the logs of the prototype revealed its utility for the case company, we did not yet confirm the positive impact quantitatively in sustainability (e.g., reduction of travel distance in load operations). Finally, although our model is supported by literature in the field, practitioner's involvement, and market search about components to implement in construction cranes, the expert's opinions contain a certain degree of subjectivity because they belong to the same construction group. A summative evaluation with a real instantiation is interesting to conclude about the utility of the artifact, but, as identified in Venable et al. (2016), additional formative evaluations can be adopted to reduce risks. Nevertheless, the case company is interested in investing in a PSS that provides multidimensional safety responsibility. Both the PSS and the revenue model are innovative for the construction sector and may contribute to its urgent call for sustainability.

Interesting directions for future research are open. The concept of pay-per-sustainable-use can be tested in other physical products and industries, for example, the use cases projected in the discussion or replacing traditional car rental with *pay-per-sustainable-mobility* that returns part of the value to the customer. Moreover, each equipment and sector of the economy has its sustainable elements to monitor (e.g., in some cases, environmental emissions or resource consumptions are more critical than safety), candidate technologies, and use cases that require additional research. Our work explored several opportunities for IoT, cloud, mobile, or GPS, but other options are also possible to extend our proposal, namely, augmented reality and artificial intelligence. It will be necessary to study the impact of pay-per-sustainable-use with end-user surveys and empirical work that support investment in this revenue model, which seems particularly interesting to foster sustainability when the PSS customer is not yet fully compromised with long-term value creation. Transforming mentalities is a significant responsibility for information systems researchers of this decade.

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