Smart wearables and construction purchasing: Challenges of bridging the digital and the physical

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Summary
This paper explores the challenges of integrating smart personal protective equipment (PPE), or digiphysical products, into construction industry procurement and quality assurance frameworks. While promising enhanced safety and efficiency, smart wearables face adoption barriers within purchasing systems ill-equipped for their hybrid nature. A literature review and a case study reveal significant gaps in evaluating these products' digital and physical components. Concluding, the research emphasizes the necessity for procurement processes that effectively bridge these realms. Further research should concentrate on developing standards for smart PPE to refine procurement and assessment processes. This will facilitate the adoption of these innovative technologies in construction.

Keywords: Construction industry, Construction safety technologies, Procurement portals, Personal protective equipment (PPE), Digiphysical products

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Introduction
In recent years, the introduction of smart wearables, or digiphysical products, has paved the way for new and innovative approaches to Personal Protection Equipment (PPE) in the construction industry. These innovative tools, ranging from smart helmets to reflexive vests equipped with sensors and connectivity features, promise to enhance safety and operational efficiency on construction sites (Rane, Choudhary & Rane, 2023). However, their integration into the existing procurement and quality assurance frameworks pose significant challenges.

Construction companies typically utilize internal webshops or procurement portals to manage the distribution of PPE among their personnel. This system ensures that all equipment meets the necessary safety and quality standards before being deployed on site (OSHA, 2004). However, the emergence of digiphysical PPE has revealed a critical gap in these processes. Traditional evaluation methods, designed for purely physical goods, falter when confronted with the hybrid nature of smart wearables, which combine tangible materials with digital functionalities such as Bluetooth connectivity and embedded computing (Basodan, Park & Chung, 2021).

The challenge primarily stems from the division of procurement responsibilities within construction firms. While the purchasing department is well-versed in assessing physical products, its expertise does not extend to the digital components of smart PPE. Conversely, IT departments, adept at evaluating software and digital solutions, lack the mandate and the means to assess the physical aspects of these products. This dichotomy results in digiphysical PPE falling into a procedural no-man's land, unable to be properly evaluated or qualified for inclusion in the procurement portals (Rasouli, Alipouri & Chamanzad, 2024).

This paper aims to explore the intersection of digital and physical realms within the context of PPE in the construction industry. By examining the challenges faced by building contractors in integrating smart wearables into their safety gear arsenals, it seeks to shed light on the shortcomings of current procurement and quality assurance processes. Furthermore, this study will investigate the gaps that hinder the effective adoption of digiphysical products in construction safety protocols. By highlighting the problems possible paths that harmonizes the assessment of both physical and digital attributes of PPE can be identified. In the long run, this facilitates that that innovation in safety equipment can be seamlessly and effectively integrated into construction projects, enhancing worker safety and efficiency (Rashidi, Woon & Dasandara, 2024).

The primary objective of this research is to explore the procurement and quality assessment challenges of digiphysical PPE in the construction industry. With an increasing reliance on smart wearables to improve safety and efficiency, this study identifies a critical gap between traditional physical product procurement and the emerging necessity for digital product assessment.

The paper begins with an introduction to the rising importance of smart wearables and digiphysical products in the construction industry, highlighting the integration challenges these innovative tools present to traditional procurement and quality assurance frameworks. It then transitions into a discussion on the research methodology, encompassing a literature review and an empirical case study focused on the implementation of a smart safety vest in Sweden. The frame of reference section delves into the inherent safety risks in construction, the potential of smart wearables to mitigate these risks, and the procurement challenges of integrating such technologies. A case study elaborates on the technological features of the smart vest and its implications for construction safety and procurement processes. The paper concludes with a discussion on the broader implications of digiphysical product integration, proposing future research directions to enhance procurement processes, quality assessment methodologies, and the adoption of digiphysical products in the construction industry.

Research approach and methodology

This study adopts a two-phase research design (Yin, 2009), blending a literature review with an empirical investigation to navigate the evolving landscape of procurement practices and smart wearables in the construction sector. The initial phase embarks on a literature review, focusing on procurement methodologies within construction alongside the innovative domain of smart wearables and digiphysical products. This review aims to chart the existing knowledge terrain, identifying where digital and physical attributes intersect and diverge.

After the theoretical groundwork, the study transitions into an empirical exploration via a case study (Voss, Johnson & Godsell, 2016) at a leading construction contractor in Sweden. The focus narrows down to an alert vest that exemplifies the digiphysical product genre, melding high-visibility physical utility with advanced functionalities, such as controllable printed lights, AI-driven motion detection, Bluetooth technology, and smartphone app integration. This vest's capacity to interface with Real-Time Traffic Information Systems (RTTI) introduces a novel safety paradigm, potentially revolutionizing on-site worker visibility and hazard awareness (Oesterreich & Teuteberg, 2016).

Empirical data collection includes participatory research, site and test observations, semi-structured interviews, review of meeting minutes, and analysis of both internal and publicly available documents. This approach facilitates a holistic understanding of the procurement assessment process for digiphysical products, pinpointing friction points and core challenges within current practices. Furthermore, this phase aims to unearth strategies that could mitigate the unique challenges posed by the dual nature of digiphysical products, proposing avenues for future scholarly inquiry.

Frame of Reference and contextual background

Construction site safety

The construction industry is marked by inherent safety risks, making it one of the most hazardous sectors. Despite stringent safety protocols, the industry continues to report a substantial number of injuries and fatalities. To take Sweden as an example, between 2014 and 2019, the industry experienced an average of 11 injuries per 1000 employees annually, positioning it as the sector with the second-highest injury rate in Sweden, closely following manufacturing. Moreover, it notably recorded the highest number of fatal accidents per year (Arbetsmiljöverket, 2021). A closer examination by Samuelsson (2019) reveals that the predominant causes of these incidents include damage from tools, body strain from repetitive movements, falls, and notably, vehicle and machine-related injuries. Although these latter injuries account for only 12 % of the total, they represent a significant 47 % of all construction site fatalities in Sweden over the last decade, underscoring the critical risk vehicles and machinery pose on construction sites (Arbetsmiljöverket, 2019).

The complexity of construction sites, where diverse professional groups such as skilled workers and machine operators coexist, demands rigorous safety measures. This complexity is compounded in road construction scenarios, where workers are not only exposed to the inherent risks of the construction environment but also to the added danger of vehicular traffic. This paper zeroes in on the particular hazards faced by road construction workers, emphasizing the intersection of construction activities and public vehicular access as a significant area of concern.

In these environments, the integration of smart PPE emerges as a potential means to enhance worker safety. Innovations like sensor-enriched vests and helmets can provide real-time monitoring of hazardous situations, track health conditions, and facilitate advanced risk management by alerting workers to imminent dangers, including the approach of vehicles (Yang, Yu, Shirowzhan, Sepasgozar & Li, 2020). These technologies, embodying the convergence of digital capabilities with traditional safety gear, offer a promising avenue to mitigate the risks associated with road construction activities.

Smart wearables in roadwork safety

The integration of digiphysical products within the construction industry marks a transformative era, blending digital innovations with tangible elements to elevate efficiency, safety, and project oversight. Technologies such as augmented reality for immersive site planning, Internet of Things (IoT) sensors for structural monitoring, and smart materials that adapt to environmental changes are pioneering a unique integration of digital and physical aspects in construction, presenting customized solutions to its inherent complexities (Awolusi, Marks & Hallowell, 2019; Basodan et al., 2021). Particularly, smart wearables like AR helmets, health monitors, and smart gloves exemplify this synergy, enhancing worker safety and efficiency through real-time data analysis, hands-free operations, and improved situational awareness (Yang et al., 2020; Rane et al., 2023). These advancements, including the fusion of smart wearables with PPE, equipped with GPS, Bluetooth (BLE), accelerometers, and gyroscopes, signify a commitment to elevating safety and operational efficiency by enabling precise monitoring of environmental and physiological parameters, thereby advancing adherence to safety standards across construction sites (Chauhan, Singh & Luthra, 2021; Rasouli et al., 2024).

Construction roadworks are inherently hazardous, with workers frequently operating in close proximity to moving traffic, elevating the risk of accidents significantly (Yang, Ozbay, Ozturk & Xie, 2015). Despite comprehensive safety measures, including the use of PPE, traffic control mechanisms, and extensive training programs, the frequency of accidents remains a concern,

highlighting the need for rigorous enforcement of safety protocols (Rao, Radanovic, Liu, Hu, Fang, Khoshelham, Palaniswami & Ngo, 2022). Road workers are particularly susceptible to incidents involving speeding civilian vehicles, contributing to a notable number of work-related serious injuries and fatalities.

In Sweden, for instance, road workers face considerable dangers, particularly from speeding civilian vehicles. Reports by the Swedish Work Environment Agency (2022) highlight a concerning number of incidents, emphasizing the urgent need for improved protective measures. Compounding this issue, research from M Sweden (2021) reveals that a mere 27 % of car drivers adhere to speed limits in roadwork zones, correlating directly to the approximately 4,000 annual roadwork-related accidents that impact road workers. This statistic not only illustrates the severe gap in safety compliance but also underscores the imperative for innovative solutions to safeguard those employed in these high-risk environments.

Smart wearables offer a promising avenue for improving safety in construction roadworks. These devices, capable of real-time communication with drivers via RTTI systems, present a novel approach to enhancing traffic safety around roadwork sites. Research by van der Heiden, Janssen, Donker & Merkx (2018) suggests that smart wearables, when integrated with RTTI, have the potential to significantly reduce vehicle speeds as drivers approach roadwork zones, thereby lowering the risk of accidents and fatalities (Ackaah, Bogenberger & Bertini, 2019). This technology not only enhances the safety of road workers by providing them with an additional layer of protection but also acts as a proactive measure in mitigating the risks posed by speeding vehicles. The implementation of smart wearables, therefore, represents a critical step forward in the ongoing effort to safeguard road workers and reduce the incidence of roadwork-related accidents.

Construction purchasing: Challenges and innovations

While the integration of smart wearables signifies a transformative leap in construction safety and efficiency, their assimilation faces procurement and quality assessment challenges, notably due to the lack of standardized evaluation frameworks for digiphysical products. These challenges underscore the necessity for an integrated assessment framework to bridge digital innovations with traditional safety measures, ensuring a smooth adoption of smart wearables. Consequently, the adoption and effective utilization of digiphysical products, including smart wearables, demand an updated procurement strategy that acknowledges their unique characteristics, thereby enabling their full potential in enhancing construction operations (Rasouli et al., 2024; Rashidi et al., 2024).

In the construction sector, purchasing plays a pivotal role in shaping competitive advantage and operational efficiency, yet its strategic importance often goes unrecognized. Large construction firms, where purchasing can represent 70 to 80 percent of turnover, view strategic purchasing as essential for optimizing cost efficiency and fostering long-term supplier relationships (Axelsson, 2005). The challenge lies in balancing the decentralized nature of construction operations, which can lead to a misalignment between project-specific requirements and overarching purchasing strategies (Dubois and Gadde, 2000), and the external reliance on a wide array of suppliers, necessitating a nuanced approach to supplier management. This involves managing a diverse supplier base, balancing long and short-term relationships, and ensuring coherence between project demands and strategic purchasing objectives.

However, the integration of innovative technologies, particularly in the realm of smart wearables and digiphysical products, introduces new challenges to construction purchasing processes. The adoption of smart PPE, which combines advanced technological features with traditional safety equipment, exemplifies the intersection of digital and physical elements in construction safety management (Yang et al., 2020; Basodan et al., 2021; Rashidi et al., 2024). These advancements necessitate a reevaluation of existing purchasing frameworks to

accommodate the unique requirements of digiphysical products, which often blur the lines between physical and digital goods.

The inclusion of smart wearables in construction safety protocols represents a significant shift towards a more integrated and technologically advanced approach to worker safety. However, the procurement of such innovative solutions poses unique challenges, often due to the lack of standardized processes for evaluating and adopting digiphysical products. The existing procurement infrastructure in many construction firms is designed to assess either purely physical or purely digital products, leaving a gap when it comes to digiphysical items. As a result, many potentially transformative technologies fail to be adopted at scale, underscoring the need for a more flexible and inclusive procurement strategy that can adapt to the evolving landscape of construction technologies.

This analysis highlights the pressing need for tailored research to bridge the gap between project-based operations and corporate strategy in the construction sector. Aligning purchasing functions with corporate strategy not only enhances operational efficiency but also solidifies the construction company's competitive positioning. The complex dynamics of buyer-supplier relationships in construction, characterized by a diverse supplier base and strategic decisions regarding long-term versus short-term engagements, further complicate the purchasing landscape, calling for a nuanced understanding and strategic approach to procurement in the context of smart wearables and digiphysical products.

Case Study: Enhancing construction safety through smart wearables

In the construction sector, characterized by high-risk environments and the ever-present potential for workplace accidents, the integration of innovative technology presents significant opportunities to enhance safety protocols and reduce incidents. This case delves into the introduction of a smart safety vest, emphasizing its technological innovations and their implications for improving construction safety. Additionally, this case examines the purchasing challenges associated with integrating such digiphysical products into existing procurement frameworks. The smart vest is designed in two versions to suit various environmental conditions and complies with EN20471:2013 class 2 safety standards. It features active lights and attachable sleeves for cooler climates, alongside a lighter build for warmer conditions.

Technological backbone and safety enhancement applications

At the heart of the smart safety vest lies an electronic collar, featuring a single-button interface that facilitates the seamless adoption of smart functionalities. The electronic collar also includes artificial intelligence (AI) for automated alarm responses, Bluetooth connectivity for effortless synchronization with a proprietary application, and the capability for over-the-air firmware updates, ensuring the vest remains current with the latest safety features and protocols.

The vest's key functionalities are designed to enhance worker safety proactively. These include AI-powered fall detection to initiate an automatic alarm, manual alarm activation through the collar button for immediate assistance, and a timer alarm tailored for operations in high-risk areas. Connection to a dedicated app further amplifies the vest's utility, enabling firmware upgrades, emergency contact configuration, customization of alert messages, control over embedded lights, and a "find my vest" feature for straightforward location tracking.

A pivotal aspect of the vest's design is its integrated lighting and AI-driven alerts, significantly improving worker visibility and safety. It effectively addresses crucial safety scenarios, such as enhancing visibility in low-light conditions and providing immediate alerts in the event of a fall. The vest's advanced lighting and motion-sensing technology play a vital role in ensuring worker visibility is maximized, particularly in environments where visibility is compromised. Upon detecting a fall, the vest not only activates its lights to alert nearby personnel but also communicates with the wearer's smartphone to notify emergency contacts, including precise location details.

Furthermore, the smart safety vest employs an app-based system to establish connectivity with RTTI, facilitating dynamic geofencing around roadwork sites. This feature creates a virtual boundary that actively communicates with approaching vehicles, issuing targeted warnings based on the vest's location data transmitted via the app. These alerts serve to inform drivers of road workers' presence and urge them to reduce speed if exceeding roadwork zone limits.

This integration marks a substantial improvement in protecting road workers, ensuring passing vehicles are cognizant of their proximity and motivated to adjust their speed appropriately. The seamless synergy between the smart vest, the app, and RTTI systems illustrates the potential of digital functionalities to bolster traditional safety measures, adopting a proactive stance in mitigating high-speed traffic risks near roadwork areas.

Integrating digiphysical innovations into construction procurement

The integration of digiphysical products like the smart safety vest into the construction industry represents a significant leap towards enhancing worker safety through technological advancement. This period of innovation, characterized by the merging of digital technologies with physical materials, poses unique challenges within traditional procurement frameworks. Conventional systems often fall short in adequately evaluating these hybrid innovations, necessitating a comprehensive reassessment of procurement strategies to effectively blend the digital with the physical aspects.

The construction industry's procurement process is methodically designed to secure the highest quality products through a series of stages, including supplier qualification, product evaluation, risk assessment, compliance checks, and performance monitoring. Each stage aims to rigorously assess suppliers' capabilities and products' adherence to quality, reliability, industry standards, and project-specific requirements, while also addressing potential risks and ensuring legal and regulatory compliance. However, this predominantly physical-focused approach frequently overlooks the digital components essential to smart wearables, highlighting a significant gap in the procurement of digiphysical products.

Addressing this oversight requires an evolved procurement strategy that establishes standardized evaluation processes for digiphysical products. Such a strategy should foster dynamic supplier relationships tailored to construction safety needs and ensure the interoperability of devices within the construction technology ecosystem. The challenges of integrating advanced wearables into safety protocols underscore the necessity for procurement practices to evolve, aligning with the industry's operational and strategic objectives.

This strategic shift in procurement practices is pivotal for promoting the widespread adoption of technology-driven safety enhancements. By advocating for a refined understanding and comprehensive overhaul of construction procurement practices, the industry can effectively accommodate the unique characteristics of digiphysical products. This not only elevates safety measures but also enhances operational efficiency across the sector, marking a significant advancement towards a more technologically integrated future in construction safety.

Discussion

In the construction industry, the advent of smart wearables, exemplified by innovations such as the smart safety vest, represents a significant stride towards enhancing onsite worker safety through digiphysical products. These products, which seamlessly merge digital functionalities with physical protective gear, offer promising solutions to longstanding safety challenges. However, the integration of such advanced technologies into construction purchasing processes, particularly their approval for listing on internal procurement portals, presents a complex array of challenges. This discussion delves into these challenges, with a focus on the digiphysical nature of smart wearables, the unique dynamics of construction purchasing, and

the strategies to bridge the gap between digital and physical in supplier and product assessment processes.

Challenges of digiphysical products in construction purchasing

The introduction of digiphysical products into the construction sector brings to the fore a crucial challenge: the existing procurement frameworks are primarily designed for either entirely physical or wholly digital products. The hybrid nature of smart wearables, which encompass both digital and physical components, therefore, finds itself in a procedural limbo. Traditional procurement processes, which evaluate the physical quality and compliance of PPE, are ill-equipped to assess the software, connectivity, and digital functionalities that smart wearables bring. Similarly, IT departments, adept at evaluating digital solutions, lack the mandate or the capability to assess the physical attributes of these wearables, resulting in a gap that hinders the effective adoption of such innovations (Rasouli et al., 2024; Rashidi et al., 2024).

Addressing construction purchasing challenges: digital and physical

The purchasing process within the construction industry is fraught with challenges that are magnified in the context of integrating smart wearables. These challenges include: strategic vs. tactical procurement gap, complex buyer-supplier relationships, and long-term vs. short-term perspectives.

There exists a significant divide between the strategic procurement at the company level and the tactical, project-level purchasing. This divide complicates the approval and listing of innovative, digiphysical products on internal webshops, as strategic procurement focuses on long-term benefits and partnerships, while project-level purchasing is driven by immediate needs and cost considerations.

The construction industry is characterized by complex, multi-layered supplier relationships, encompassing a vast array of products and services. The integration of smart wearables into the procurement process requires navigating these complex relationships and establishing new criteria for evaluating and selecting suppliers of digiphysical products.

The conflict between seeking long-term benefits through innovation and focusing on short-term, cost-driven purchasing decisions poses a significant challenge. The introduction of smart wearables into internal procurement portals necessitates a shift towards a more long-term perspective, valuing the safety, efficiency, and innovative benefits these products offer over immediate cost savings.

The dual nature of smart wearables necessitates a procurement process that can effectively evaluate both their digital and physical components. Current processes, which treat digital and physical products separately, leave digiphysical products in a sort of no-man's land. Developing a unified framework for assessing these products requires a holistic approach that considers the interoperability of devices, the compatibility of software with existing IT infrastructure, and the physical safety and compliance of the wearables. This approach should be informed by industry standards, best practices, and collaborative efforts between procurement, IT, and safety departments.

Theoretical and practical implications

Linking these challenges and proposed strategies to the existing body of knowledge highlights the importance of adaptive and integrated procurement practices. The literature underscores the need for construction firms to evolve their procurement strategies to accommodate the unique requirements of digiphysical products. Practical implications include the development of new supplier assessment criteria, training for procurement staff on evaluating digital functionalities, and the establishment of cross-departmental teams to manage the procurement of smart wearables.

In conclusion, the integration of smart wearables into construction purchasing processes represents a frontier of innovation fraught with challenges. Overcoming these challenges requires a concerted effort to bridge the gap between digital and physical, align strategic and tactical procurement objectives, and navigate the complex landscape of buyer-supplier relationships. By addressing these issues, construction firms can harness the full potential of digiphysical products to enhance worker safety and operational efficiency.

Conclusions and further research

This research has illuminated the procurement challenges and opportunities brought forth by the integration of digiphysical products, such as smart PPE, into the construction industry. By delving into these complexities, this study underscores the transformative potential of these technologies in enhancing construction site safety and operational efficiency. Specifically, it highlights the critical role of innovations like alert vests in advancing worker safety in construction road works, advocating for a modernized approach to safety measures and procurement practices that prioritizes integration and efficiency.

The empirical investigation into the procurement and quality assessment processes for digiphysical products reveals a notable disconnect, posing significant challenges but also presenting opportunities for innovation and improvement. To navigate these challenges, this study proposes three potential pathways for future development:

1. A unified process:
   Advocating for an integrated workflow for procurement and quality assessment that merges the digital and the physical, aiming to streamline operations and enhance efficiency.
2. Parallel but coordinated/linked processes:
   Suggesting enhancements in coordination or links between existing parallel processes for digital and physical products, to foster alignment and communication.
3. Sequential processes with iterative feedback:
   Proposing a structure that allows for dynamic feedback between sequential processes for the digital and physical parts of the products, enhancing adaptability and effectiveness.

The exploration of these pathways, particularly the sequential approach, prompts critical considerations regarding the order of procurement and quality assessment processes, each bearing unique advantages and challenges. As this study navigates the complexities of integrating smart wearables into construction procurement, there are also more technical areas of inquiry. One example of this is the need to develop universal standards for smart PPE. The establishment of universal standards for the design, testing, and implementation of smart PPE is crucial. Such standards will ensure the effective and widespread adoption of these technologies, fostering a safer and more efficient working environment (Rasouli et al., 2024; Rashidi et al., 2024).

By addressing these outlined challenges and focusing on the suggested areas for further research, the construction industry can fully leverage the benefits offered by digiphysical technologies, thus promoting a safer and more efficient working environment. The integration of digiphysical PPE into construction presents not only procurement and assessment challenges but also a profound opportunity for research and innovation. Developing standardized procedures for evaluating these technologies is essential to maximizing their safety benefits, necessitating focused research to update procurement processes and assessment methods for digiphysical PPE in the construction industry.

In conclusion, this study contributes to the ongoing dialogue on the integration of innovative safety technologies in the construction industry, setting a foundation for future research aimed

at enhancing procurement processes, quality assessment methodologies, and the effective adoption of digiphysical products. The journey towards a safer, more efficient construction industry is ongoing, and through continued exploration, evaluation, and adaptation, significant strides can be made in realizing the full potential of these groundbreaking technologies.

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