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SUSTAINABLE INNOVATION PROCESSES IN THE ASPHALT PAVING SECTOR: A SYSTEM INNOVATION APPROACH

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The asphalt paving sector is committed to achieving sustainability targets and the adoption of innovations, such as alternative materials and more efficient production and construction processes, offer a way forward. Despite the progresses already made, widespread implementation of such innovations is lagging, mainly due to social and institutional aspects of the transformation such as policies and regulations, cultural values and norms, lack of awareness and knowledge. This study employs a system innovation approach to determine which key elements shape sustainability innovation processes in the asphalt paving sector. To identify elements, we critically compare empirical patterns that were identified using the Dutch asphalt sector as case study with theoretical patterns that resulted from a literature review on drivers and barriers to sustainability and innovation. We conclude that the system innovation process is determined by a set of fifteen elements including institutional rules, inter and intra-organizational dynamics, and actors' roles. This set of elements can be used to build the structure of the system and explore its dynamics and enable the sector to reach more efficient innovation processes.

Keywords: Asphalt paving; socio-technical systems; innovation; sustainability

INTRODUCTION

The asphalt paving sector is committed to moving towards a more sustainable path by adopting innovations, such as alternative materials and more efficient production and construction processes (United Nations, 2020). However, the widespread implementation of such innovations is lagging. To better understand the implementation of sustainable innovations, we adopted a system innovation (SI) approach to conceptualize the process as a socio-technical system (STS) (Elden *et al.,* 2004). Academics and practitioners in the construction sector recognize the relevance of employing STS to approach sustainability and innovation challenges (Li *et al.,* 2019; Pelle, 2021). However, most studies in the construction field tend to focus on the characterization of the technical dimension, which is frequently considered as an endogenous process in single organizations (Arshad *et al.,* 2021; Ershadi *et al.,* 2021). Although the social dimension in STS is recognized, it is usually considered as an

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external element when analysing innovation, leading to a poor understanding of the influence of other as institutional rules, cultural values, and actors' preferences in the implementation of innovations in the engineering field.

Insights from SI literature highlight that considering the dynamics of both technical and social dimension is relevant for promoting the implementation of sustainable innovation, specifically, the interactions among the actors involved in process success R&D, production, market, and policies (Sour's and Roelofs, 2014). The decisions and activities made by the actors of the system shape its structure which accounts for its ability to respond autonomously, adapt to the context, and be steered towards a goal (Geels and Kemp, 2007). In other words, technological innovations are important to achieve sustainability targets, but they require a link to the social dimension (actors, networks, and institutional rules) since the latter establishes the structure of STS and is responsible for the capacity of the system for fulfilling its purpose (Organisation for Economic Co-opertaion and Development OECD, 2015; Smith *et al.,* 2010). Consequently, a proper understanding of the social elements and their link to the technical elements is needed to strengthen the implementation of sustainable innovations.

Our study aims to identify the elements that shape the decisions and actions of the actors involved in the innovation process by examining the system innovation processes in the public sector domain. To accomplish this, this study applies pattern matching to combine insights from a case study in the asphalt paving sector in the Netherlands (Ruiz *et al.,* 2023) with broader insights from the literature on system innovations for exploring the key socio-technical elements in the asphalt paving sector within the context of developing and adopting technological sustainable innovations.

METHOD

We used pattern matching to identify and define the most influential elements that facilitate or hinder the implementation of sustainable innovations in the asphalt paving sector. We compared empirical patterns with theoretical patterns to identify matches and relationships between them (Yin, 2015). First, we identified a set of empirical elements based on insights collected through interviews with experts in a case study of sustainability innovation in the Dutch asphalt paving sector as described in Ruiz *et al. (*2023). We selected the asphalt paving sector in the Netherlands as a case study because it offers the opportunity of analysing the implementation of innovation in a complex context where both the public and private sectors are responsible for delivering public services. Specifically, the Netherlands has a dense road network of high quality, that is mainly managed by public authorities, which commission parts of the private sector to carry out construction and maintenance work (Government of the Netherlands, 2022). The country is committed to reducing CO2 emissions, with sustainability innovations being encouraged in various sectors, including the infrastructure sector (Ministry of Infrastructure and Water Management, 2020). Our case study research revealed that "testing and validation" and "scaling-up" require a higher level of interorganizational interactions than earlier stages where problems are identified, ideas developed and prototyped. Therefore, we decided to focus our analysis on these stages.

Second, for identifying the theoretical elements, we conducted a literature review on socio-technical system elements and drivers and barriers to innovation and sustainability. We selected 26 articles for our critical literature review based on several criteria. We focused on recent publications within the last 10 years to ensure

that our review captured the most up-to-date research in the field. Additionally, we limited our review to articles that addressed the social dimension. Furthermore, the literature review is conducted using a "snowball sampling" approach (Wohlin, 2014), which involves selecting key studies and then identifying further relevant sources through their reference lists. This method is useful for efficiently assessing the range of research resources related to a particular subject and for the effective retrieval of pertinent literature (Gordon *et al.,* 2023; Greenhalgh and Peacock, 2005).

Third, to define the set of key elements, we employed pattern matching to compare the empirical elements observed in our case study with theoretical elements identified in the literature review. By examining similarities and mismatches between them, we established connections that helped us to identify the key elements relevant to our research objective. This process allowed us to validate elements that have been identified in previous studies and uncover elements that have not been explicitly addressed and generate a deeper understanding of the elements influencing the innovation process. Additionally, we adopted three categories for grouping the identified elements: institutions, actors, and interactions. The three categories reflect a common view of system innovations across different disciplines; system innovation processes are shaped by the variety of interdependent actors interacting in social networks and institutional contexts (Elzen *et al.,* 2004; Suurs and Roelofs, 2014).

Finally, we conducted a synthesis of elements based on the pattern matching. Specifically, we merged the set of empirical elements according to the description of the elements provided in the articles reviewed. For instance, elements such as knowledge exchange, collaboration, and communication initiatives were merged into collaboration since they represent different aspects of the same overarching concept, emphasizing the importance of information sharing, cooperative efforts, and effective communication in driving the implementation of sustainable solutions, i.e., they represent similar types of interactions among actors.

FINDINGS

This section describes the structural elements identified in the process that led to implementing sustainable innovations in the Dutch asphalt paving sector. First, we matched the empirical elements with the theoretical ones to identify those that were consistently mentioned in other studies. For example, the case study showed that accessibility to the testing location was an influential element in the Dutch asphalt sector. This element was then compared with the findings reported in the literature and it was found that 35% of the studies reviewed also identified it as a key element.

Table 1 presents the results of the pattern matching, with the first column showing the three pre-defined categories (i.e., institutions, actors, and interactions), plus a fourth one (i.e., "other") for those elements that did not fit in the previous three. The second column lists the 24 empirical elements identified in the case study, and the third column the literature sources (including the percentage of the 26 articles) in which the corresponding empirical element was highlighted. Based on the pattern matching results, we defined a consolidated list of 15 elements in the four categories. In the subsequent sections, we provide a concise explanation of each category, specify the elements within the category, including the percentage of papers in the literature review that identified them, and demonstrate its application in the context of asphalt.

Institutions

Institutions refer to set of rules, norms, and conventions that govern the actors' behaviour in a particular context. They can be formal, such as laws and regulations or informal, such as social norms and shared values (Hodgson, 2006). The first element in this category is "legal and policy factors", where actors adapt their behaviour based on a law or practice established by other actors or society. This type of element was identified in 77% of the studies reviewed. The studies particularly stress that regulatory uncertainties, inadequate policies, and incentives can hinder the implementation of sustainable innovations. In the Dutch asphalt paving sector, the innovation process is extremely shaped by policies and regulations. For instance, recycled materials and low-temperature asphalt mixtures are dominant among innovations because of being strongly promoted and requested by road authorities.

The second element is the "mindset", which was identified in 62% of the studies reviewed. It is influenced by factors such as awareness and consciousness, resistance to change, values, beliefs, trust, and fear. Actors in the asphalt paving sector are reluctant to accept radical innovations and focus on short-term project perspectives in decision-making which is also hindering the progress towards sustainability. The third element in this category is "conservative assessment criteria". The assessment criteria are the set of rules or norms to determine the potential of sustainable innovations. Most studies highlight assessment criteria as an influential element. However, 27% of the studies specifically mentioned that the challenge is that the current criteria in different fields tend to prioritize stability over change, making it difficult to introduce new technologies. In the asphalt paving sector, the main challenge regarding the conservative assessment criteria is that sustainable innovations are assessed following standards developed decades ago and are expected to perform technically in the same way as traditional asphalt materials.

The last element of the institutions is "lack of harmonization" across and within levels of the system. It was identified in 58% of the studies, which highlighted the lack coherence and consistency in policies, procedures, focus areas, and standards. In the Netherlands, sustainability standards and assessment criteria can vary from project to project or from client to client. This leads to confusion among actors and can create uncertainty, especially for contractors who may not know where to focus their resources.

Interactions

The elements in this category represent the main ways in which actors across the system interact and communicate. The main element is "collaboration", which was found in 54% of the studies (including communication initiatives and knowledge exchange). This percentage shows that collaboration with suppliers, participation in R&D networks, co-creation of products and services, and closer interaction and networking can lead to successful sustainable innovation implementation. In the asphalt paving sector, actors are aware of the need of collaborating, but most of these happen in the form of best practices exchange. This alone is insufficient to generate comprehensive joint efforts. To effectively accomplish the implementation of innovations, the sector must bridge the gap between practice exchange and robust collaborative actions.

Additionally, several other types of "inter-organizational interactions" were also identified in 23% of the studies. This includes communication channels, and relationships with suppliers, clients, public organizations, and communities. The literature highlights that inter-organizational interactions tend to be a challenge,

especially when the relational power lies in one or a few organizations. This is the case in the asphalt paving sector, where the public actors are dominant, generating a relational power imbalance, which leads the private actors to face challenges in gaining support for innovating.

The third element in this category is "intra-organizational interactions" and in particular, the hierarchical ones that require interactions at different levels of the organization. It was identified in 35% of the studies reviewed, which highlights that many organizations struggle to adopt sustainable innovations due to inappropriate organizational structure that leads to poor communication. In the asphalt paving sector operational-level actors, such as the specialized staff, find it difficult to exert influence at the strategic level. This calls for an improvement of vertical communication channels. Emphasizing the need for cross-functional teams that helps to coordinate and engage multiple actors.

Actors' Roles

The last category includes five key roles in innovation: managers, specialized staff, framework setters, evaluators, and coordinators. The first one is the role of "managers", which was mentioned in 62% of the studies as crucial in the implementation of sustainable innovations. Studies have shown that top managers' support is essential for sustainability innovation processes. The decentralization of decision-making within top management teams means that actors with leadership powers have a significant impact on the sustainability dimension of any organization. In the asphalt paving sector, top managers were identified as key actors in the innovation process, particularly asset managers since they decide which kind of projects would be developed and when.

The second key role is the "specialized staff", which was identified in 54% of the studies reviewed. Usually, it was mentioned as a barrier, due to the lack of skills and training, and deficiency in knowledge. In the asphalt paving sector, the specialized staff is directly involved in the development of assessment methods and criteria in the testing and validation and scaling-up stages. Specifically, LCA and pavements experts provide inputs in these stages. However, the specialized staff usually serves as consultants but are not the ones making the decisions. The involvement of specialized staff in decision-making processes can help in developing innovative solutions and identifying opportunities for sustainable practices.

The third role identified as a key structural element is the "framework setters", particularly public authorities. According to 27% of the studies, governmental bodies serve as the main driver for implementing sustainable practices in industries, since they drive most regulations, policies, and incentives. In doing so, they facilitate or make more difficult the shift towards a more sustainable paths and provide a clear direction for the rest of the actors involved in the innovation process. In the asphalt paving sector, the framework setters, especially road authorities, play the most significant role in the overall process, in the sense that they develop sustainable policies and issue targets that shape all the stages in the process. The frameworks setters' actions can help levelling the playing field, encouraging the sector to adopt sustainable innovations and reducing the competitive disadvantage faced by early adopters.

Another key role is the "evaluators", who play a crucial role in monitoring and assessing the implementation of sustainable innovations. Evaluators as a role were only identified in 8% of the studies. However, one of its main functions “monitoring”

was mentioned in 31% of them. Evaluators are responsible for creating new metrics and tools to measure the impact of innovation on the performance of systems. Through their monitoring and evaluation activities, they provide the necessary data that systems need to adapt and reorient themselves toward sustainability paths. In the asphalt paving sector, the evaluator is one of the main roles along with frameworks setters and managers, as they are the ones assessing the potential of sustainable innovations. Basically, they determine which innovations move to further steps in the innovation process. Evaluators help identify gaps and potential areas of improvement in sustainable innovation implementation, and their feedback is essential to achieve the targets.

The last key role is the "coordinators", which was mentioned in 12% of the studies. According to the literature, coordinators act as a facilitator in bringing together diverse actors such as governments, contractors, and communities to collaborate toward achieving common sustainability goals. They help build trust and communication channels among actors, create a shared understanding of challenges and opportunities, and coordinate joint actions. In the asphalt paving sector, the coordinators' role is mostly played by third-sector actors (e.g., the network for transport, infrastructure, and public spaces and research institutions), who are mostly involved in the testing and validation stage. Coordinators should take part in the entire process, connecting different actors to proactive and collaborative platforms and making a coherent combination of local and national action plans.

Other

The final category includes three elements that could not be grouped into one single category but were consistently highlighted in the literature. The first element is "financial benefits", which were mentioned in 62% of the studies reviewed. It was consistently mentioned that sustainable innovations often require high investments, and the benefits are hard to monetize or only noticeable in the long term. In the asphalt paving sector, profit always plays a role when making decisions in the innovation process. For example, an innovation with great potential of contributing to emissions reduction is not considered for further development if it does not bring profit for the companies.

Another element identified is "large-scale implementation", which was associated with market creation. This element was mentioned in 54% of the studies reviewed, highlighting that to ensure the success of sustainable innovations, it is essential to create a favourable market environment. The literature highlights that this can be done by signing agreements among different industries and creating a temporarily protected niche market. In the Dutch asphalt paving sector, the sustainable innovation process is considered successful when the innovation is implemented in multiple large-scale projects. An innovation that is implemented at that scale can guarantee high-quality products and ensure profits, which further incentivizes the contractors.

The last element is "accessibility of testing locations", which refers to the ease of locating and accessing sites where sustainable innovations can be tested and demonstrated. It allows researchers and innovators to assess the effectiveness and feasibility of their solutions and to directly analyse structural elements in the context of the innovation process. Around 35% of the studies highlighted challenges related to accessibility to testing locations, such as the difficulty in finding suitable locations for research as well as an insufficient number of trials and demonstration projects. According to the empirical patterns, this is because in the asphalt paving sector, access

to testing locations can only be ensured through collaboration among public, private, and third sectors, which can be challenging due to conflicts of interest. being the key interaction in the process.

Table 1: Pattern matching- Empirical elements contrasted with theoretical elements.

Category	Empirical elements	Literature review
Institutions	Sustainability targets	3, 5, 8, 15, 19, 21, 26 (27%)
	Lack of harmonization in policies and procedures	1-5, 7-10, 13-15, 17, 18, 20 (58%)
	Conservative assessment criteria	4, 5, 7, 10, 13, 19, 20 (27%)
	Project perspective in decision-making	15, 19, 22, 25, 26 (19%)
	Legal and policy factors	1-6, 8-16, 18, 19, 21, 22, 23 (77%)
	Misalignments among levels in the system	3, 5-7, 9, 17, 19, 22, 23 (35%)
	Mindset (trust, fear, willingness)	1,2, 5-7, 8-11, 13,14, 16, 18, 19, 21-23 (62%)
Interactions	Collaboration	3, 6, 7, 10, 14, 18, 22 (27%)
	Best practices exchange	5, 12, 15, 17, 18, 22 (23%)
	Communication initiatives	1,4, 7, 10, 15, 17, 22, 25 (31%)
	Inter-organizational interactions	4, 7, 17, 20, 22, 25 (23%)
	Hierarchical relationships (Operational and strategic level)	3,6, 7, 11, 16, 17, 22, 25, 26 (35%)
	Competition for steering innovation	2, 6, 8, 9, 11 (19%)
Actors' roles	Public sector as a framework setter	2, 5, 7, 9, 11, 22, 25 (27%)
	Public sector as a client	3, 6, 11, 19 (15%)
	Public sector as evaluator	3, 8 (8%)
	Third parties as evaluators	0%
	Managers	3, 4, 6-8, 10, 11, 14-16, 18, 19, 22, 23, 25, 26 (62%)
	Association/ groups as coordinators	17, 22, 23 (12%)
	Specialized staff	2-7, 9, 11, 14-16, 18, 24, 26 (54%)
	Monitoring (actor's role)	5-7, 13, 14, 22, 25, 26 (31%)
Other	Accessibility to testing locations	5, 9, 13, 15, 21-25 (35%)
	Large scale implementation/ market acceptance	3-6, 9, 10, 12, 13, 20, 21, 23-26 (54%)
	Financial benefits	2-6, 9-13, 16, 18, 20, 21, 23, 24 (62%)

Note: 1=(Aktas and Ozorhon, 2015); 2=(Alsanad, 2015); 3=(Atafo-Adabre *et al.,* 2020); 4=(Cardoso *et al.,* 2023); 5=(Chan *et al.,* 2016); 6=(Dhull and Narwal, 2016); 7=(Ershadi *et al.,* 2021); 8=(Giunipero *et al.,* 2012); 9=(Gordon *et al.,* 2023); 10=(Hill *et al.,* 2023); 11=(Hinrichs and Wettlin, 2019); 12=(Hoicka *et al.,* 2022); 13=(Hübel and Schaltegger, 2022); 14=(Hussain *et al.,* 2016); 15=(Kanda *et al.,* 2022); 16=(Karji *et al.,* 2020); 17=(Manny, 2023); 18=(Mathivathanan *et al.,* 2021); 19=(McMurray *et al.,* 2014); 20=(Munyasya and Chileshe, 2018); 21=(Nemoto *et al.,* 2023); 22=(Organisation for Economic Co-opertaion and Development OECD, 2015); 23=(Oeij *et al.,* 2019); 24=(Pizzol *et al.,* 2022); 25=(Wang *et al.,* 2018); 26=(Wesseling *et al.,* 2022).

CONCLUSIONS.

This study aimed to identify the elements that influence the implementation of sustainable innovations in the asphalt paving sector, an integral part of the construction industry, in the Netherlands. Our study offers insights into socio-technical elements shaping the innovation process in the asphalt paving sector, an

integral part of the construction industry. We focused on the testing and validation and scaling-up stages of the process, as they involve complex interactions among different actors and levels of the system. Based on the pattern-matching process, we identified 15 elements that play a critical role in the innovation process, which were classified in four categories: (1) institutions, which include legal and policy factors, mindset, conservative assessment criteria, and harmonization; (2) interactions, consisting of collaboration, inter-organizational, and intra-organizational interactions; (3) actors' roles, specifically, the roles of managers, specialized staff, evaluators, framework setters, and coordinators; and (4) other, which include financial benefits, large-scale implementation, and accessibility to testing locations. Overall, the findings highlight the need for systemic approaches for redistributing organizational functions and actors' roles to facilitate and improve the efficiency of the implementation of sustainable innovations. This aligns with the findings of Lee *et al. (*2021) who identified the lack of defined roles and responsibilities among actors as a main cause of limiting guidance in implementing sustainability strategies in projects.

Our study contributes to the understanding of the socio-technical elements that influence the implementation of sustainable innovations in the construction sector and other project-based industries that provide public services. It highlights the importance of analysing the institutions, interactions, and actors' roles. Specifically, the findings underline the need of a proper understanding of roles among actors at distinct levels of the system to improve effectiveness of sustainable innovations and ensure that the systems continue to meet their intended goals over time. Furthermore, our findings can help policy and decision makers, particularly in the asphalt paving sector, to identify the key structural elements that may hinder the implementation of sustainable innovations. By doing so, the transportation infrastructure sector is in a better position to design and construct infrastructure systems that can respond and adapt to changing social and environmental contexts, thereby leading to more sustainable and resilient solutions.

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