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SUSTAINABLE PRODUCT-SERVICE SYSTEM USING THE R-PSS METHOD: RECYCLED ASPHALT PAVEMENT CASE

SISTEMA PRODUCTO-SERVICIO SOSTENIBLE MEDIANTE EL MÉTODO R-PSS: CASO DE PAVIMENTO ASFÁLTICO RECICLADO

Stela Xavier Terra🗁[1], Gustavo Gregory[1], Márcia Elisa Echeveste[1], Maria Auxiliadora Cannarozzo Tinoco[1], Carolina Melecardi Zani [2]

[1] *Universidade Federal do Rio Grande do Sul: Porto Alegre, Rio Grande do Sul, BR*

[2] *University College London, UK*

🗁 stela.xavier.terra@gmail.com

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ABSTRACT. The global trend of integrating recycled raw materials into asphalt mixtures is increasing due to its environmental benefits. However, awareness about the comparable or superior performance of these mixtures compared to those made solely from virgin materials remains limited. This study aims to introduce a sustainable Product-Service System (PSS) using the Requirements Engineering approach in an asphalt plant industry through a method named R-PSS (Requirements - Product-Service System. Our solution facilitates greater incorporation of Recycled Asphalt Pavement (RAP) in asphalt production, offering sustainability advantages such as reduced virgin material consumption, partnerships with local suppliers, and improved economic efficiency. We evaluated the solution's impacts on environmental, social, and economic sustainability within the PSS. The assessment revealed significant benefits, including a reduced environmental footprint and an extended system lifespan. These results highlight the importance of adopting a Circular Economy approach that meets market needs while adhering to Environmental, Social, and Governance (ESG) principles.

Keywords: Requirements Engineering, PSS, R-PSS, ESG, Circular Economy.

RESUMEN. La tendencia global de integrar materias primas recicladas en mezclas asfálticas está en aumento debido a sus beneficios ambientales. Sin embargo, la conciencia sobre el rendimiento comparable o superior de estas mezclas en comparación con las compuestas únicamente de materiales vírgenes sigue siendo limitada. Este estudio tiene como objetivo introducir un Sistema Producto-Servicio (PSS) sostenible utilizando el enfoque de Ingeniería de Requisitos en la industria de plantas de asfalto a través de un método denominado R-PSS (Requisitos - Sistema Producto-Servicio). Esta solución facilita una mayor incorporación de Pavimento Asfáltico Reciclado (RAP) en la producción de asfalto, ofreciendo ventajas de sostenibilidad como la reducción en el consumo de materiales vírgenes, la creación de alianzas con proveedores locales y una mayor eficiencia económica. Evaluamos los impactos de la solución en la sostenibilidad ambiental, social y económica dentro del PSS. La evaluación reveló beneficios significativos, incluyendo una reducción de la huella ambiental y una mayor vida útil del sistema. Estos resultados subrayan la importancia de adoptar un enfoque de Economía Circular que satisfaga las necesidades del mercado y cumpla con los principios Ambientales, Sociales y de Gobernanza (ESG).

Palabras claves: Ingeniería de Requisitos, PSS, R-PSS, ESG, Economía circular.

1 INTRODUCTION

The use of recycled raw materials in asphalt mixtures, known as recycled asphalt, is an increasingly adopted approach worldwide due to its environmental and economic benefits. The incorporation of recycled raw materials in asphalt mixtures reduces the need for virgin material extraction, decreases waste disposal, and contributes to the sustainability of the asphalt pavement industry (GUATIMOSIM et al., 2016).

In the Brazilian context, recycled asphalt can be used in the base layer and the wearing course of asphalt pavement. Hot mix asphalt (HMA) is one of these layers' most used asphalt mixtures. HMA consists of aggregates (crushed stone, sand, gravel), asphalt cement (AC), filler (limestone, cement), and additives (PEREIRA et al., 2022).

Asphalt cement, the primary constituent of HMA, is derived from non-renewable raw materials and contributes to as much as 90% of the energy consumption associated with asphalt manufacturing (MARINKOVIĆ et al., 2014). Guatimosim et al. (2016) advocate incorporating reclaimed asphalt pavement (RAP) in asphalt layers as a viable alternative to diminish the reliance on virgin raw materials. Asphalt pavement milling produces RAP, the primary by-product of pavement restoration (OLIVEIRA et al., 2022).

Incorporating recycled asphalt into asphalt mixtures requires comprehensive studies and laboratory assessments to establish technical viability and optimal parameters. This is essential because the recycled asphalt must adhere to specific criteria related to compaction, density, uniformity, susceptibility to water, longevity, and resilience modulus (ZHANG & ZHENG, 2021). Other relevant constraints include logistical expenses, available production area, time and variety of quality tests, and issues related to water contamination and retention within the asphalt (TARSI, TATARANNI & SANGIORGI, 2020).

These considerations ensure the recycled asphalt mixture meets the required standards and performance criteria for sustainable and long-lasting pavement. Asphalt mixtures with RAP exhibit equal or better performance than entirely virgin mixtures while also reducing energy consumption and greenhouse gas emissions (NAPA, 2021). Finally, the search for more sustainable asphalt mixtures, with reduced use of non-renewable raw materials, contributes to a more symbiotic relationship with nature (MILAD et al., 2022).

Regulation advancements can significantly influence the integration of by-products within the pavement industry. As an example, a resolution from Brazil's National Department of Infrastructure and Transportation (DNIT) mandates the utilisation of RAP in road renovation, capacity augmentation, and expansion initiatives (DNIT, 2021a), albeit without specifying a minimum content requirement. This regulation necessitates the inclusion of RAP in pavement layers or new asphalt concrete, indicating a prevailing market trend favouring the assimilation of RAP in asphalt mixtures. Consequently, the presented challenge of investigating technologies for incorporating RAP into asphalt mixtures within the Brazilian industry holds implications for environmental, social, and governance considerations. This includes deliberations about adherence to local rules and regulations.

In this sense, the aim of this study is to introduce a sustainable solution that enhances the use of recycled asphalt within the Brazilian asphalt plant manufacturing industry by mapping requirements and processes and developing a value proposition through the application of the Requirements - Product-Service System (R-PSS) method (ECHEVESTE et al., 2020).

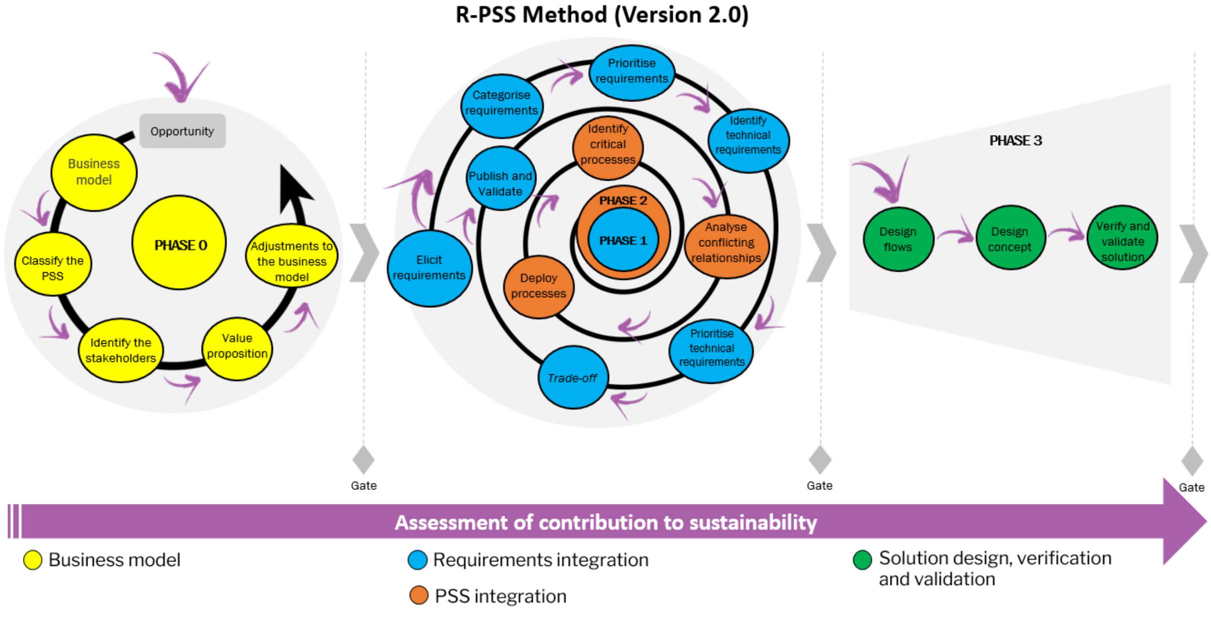
2 METHOD

This section offers a concise overview of the methodological steps undertaken in this research, which align with applying the Requirements-Product-Service System (R-PSS) method. The R-PSS methodology was formulated by Echeveste et al. (2020), drawing insights from the authors' collaborative discussions and insights gained from the original artifact's implementation in real-world business studies. Figure 1 presents an enhanced rendition of the R-PSS methodology as a navigational guide. The R-PSS approach primarily encompasses two fundamental principles: design models and stage-gates.

The first principle revolves around the design process structure for building a Product-Service System (PSS) according to the R-PSS method encompassing three distinct structures: (i) First, a circular-type model recognises that the design process is not a linear path but rather a continuous cycle of exploration, experimentation, evaluation, and adjustment. It encourages flexibility and adaptability, allowing researchers to revisit and refine their approach as new information emerges. (ii) Second, a spiral-type model that is an iterative design process with an emphasis on continuous learning and refinement. It involves repeated cycles of planning, research, prototyping, and evaluation (KHAKUREL et al., 2019). Each cycle builds upon the previous one, incorporating feedback and new insights to enhance the project outcomes (BOEHM, 1988). (iii) Third, a scale-up type model allows for increasing the size or scope of a project (TIPPMANN et al., 2023). It involves taking a concept, process, or technology that has been successfully studied on a delimited scope and expanding it to a larger scope (goal) (TIPPMANN et al., 2023). This is often done to assess feasibility, performance, and potential challenges that may arise when operating on a broader scale (DRUMMOND & THOMPSON, 2018).

The second premise alludes to the "Quality gates" approach introduced by Pahl & Beitz (1996). The roadmap of the R-PSS method comprises three cycles and three gates, one at the end of each cycle. We strongly advise including these gates as a minimum requirement. The first gate consists of completing Phase Zero ("Business Model"). This means the first cycle is ready to move on. The same meaning for completing Phases One and Two ("Requirements integration" and "PSS integration", respectively), which indicates the spiral process is ready to move onto the last phase, Phase Three ("Solution design, verification and validation"). The final gate, achieved by completing Phase Three, may lead to either closing the project or restarting Phase Zero to continuously improve the Business Model.

FIGURE 1 – Roadmap of application of the R-PSS method (Version 2.0)



SOURCE: Authors

During Phase Zero, the employed tools were instrumental in organising and communicating project ideas to the case company under study. Subsequent to establishing the business model, an extensive exploration was carried out to enhance comprehension of the PSS, encompassing its life cycle and stakeholders. In Phase One, the emphasis was on identifying and prioritising the solution requirements for the examined PSS. Moving on to Phase Two, the focus shifted to the meticulous mapping of the processes related to the PSS solution. Phase Three encompassed the comprehensive design of the entire solution, encompassing the flows and conceptual framework. This design was subsequently subjected to verification, validation, and a thorough assessment of its impact on sustainability, spanning from the initial business model to its eventual establishment as a fully consolidated PSS solution.

3 RESULTS

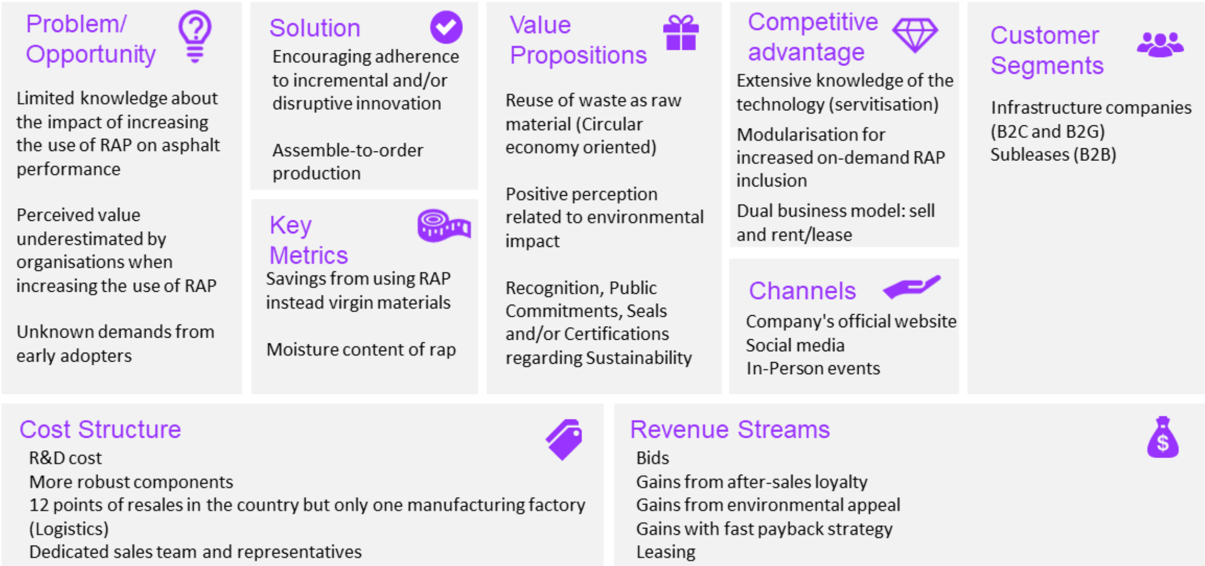
3.1 GRASPING THE BUSINESS MODEL, PSS TYPE, STAKEHOLDERS, AND VALUE PROPOSITION (PHASE ZERO)

The company under study (Company X) holds a prominent position in the Brazilian market for mobile asphalt plants, leveraging advanced technologies and engaging in dialogue with customers to provide sustainable equipment and minimise environmental impacts. Currently, their technology enables limited utilisation of RAP. However, the company anticipates potential progress in the national regulatory framework and in the demand of its customers. This encourages them to explore opportunities for further advancement in incorporating RAP into their equipment and processes.

To better understand the current business model and align expectations for the development of a sustainable PSS, we developed a project charter (confidential), following a Lean Canvas approach (PERALTA et al., 2020). Lean Canvas (Figure 2) depicted the initial solution's business model in response to the problem/opportunity identified in this study. These tools were exhaustively deliberated upon and validated through comprehensive discussions during meetings with Company X.

It is imperative to gain a comprehensive understanding of several facets to strategically position the technology within the market and discern its adaptation requisites. This includes comprehending the availability of RAP in Brazil, how RAP integration affects asphalt production operations and the overall life cycle of asphalt, and what strategies to effectively identify and convey the added value to customers. These factors are pivotal in outlining the essential research and adjustments needed to implement the technology successfully.

FIGURE 2 – Lean Canvas of the studied case



SOURCE: Authors

Drawing from the established business model, the proposed PSS solution for the asphalt plant company was categorised as a product-oriented PSS, as defined by Tukker (2004). This classification is attributed to the involvement of selling a mobile HMA plant, which functions as a technological product designed for producing asphalt mixtures with higher RAP proportions.

Introducing a technology that facilitates the incorporation of a higher percentage of RAP into asphalt mixtures presents a notably sustainable alternative when contrasted with the current choices available in the Brazilian market. In order to evaluate the viability of this solution, it is imperative to take into account the pivotal stakeholders within the pavement industry. This is because the implementation of this innovative solution entails alterations not only in the physical product itself (tangibles) but also in the accompanying services and intangible aspects.

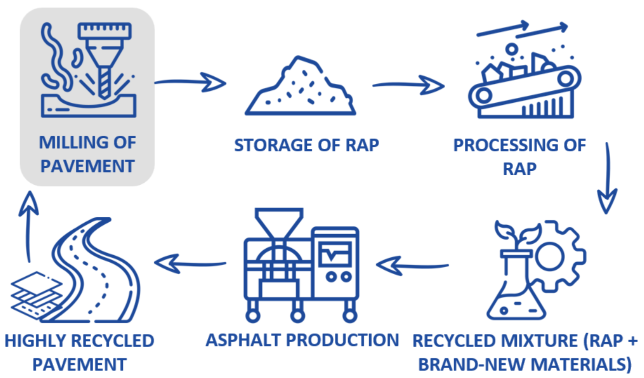
In relation to alterations within the product, the technology needed to elevate the proportion of RAP in asphalt production necessitates the incorporation of more resilient materials during the fabrication of asphalt plant equipment. Furthermore, this entails the improvement of energy efficiency and the integration of digital technologies to amalgamate services with the physical interface.

Conversely, changes in services focus on meeting customer expectations by guiding the optimised use of the plant. This requires a comprehensive understanding of market needs and customer preferences. Such support is crucial due to the complex functionality of the equipment, which involves various physical and chemical processes. For instance, in scenarios where a greater proportion of RAP is integrated, the variance in grain sizes can induce catalytic effects that influence the physical and chemical attributes and performance of the asphalt mixture. As a result, refining the process might entail the incorporation of additional reactive components at specific temperatures, among other variables that must be taken into account. By addressing these considerations, the solution has the potential to significantly enhance the sustainability and performance of asphalt production in the Brazilian market.

The aim of mobile HMA plant equipment is to produce an asphalt mixture that incorporates RAP for road pavement purposes. Its life cycle begins with milling existing pavements to acquire RAP, as depicted in Figure 3. Following this, the obtained RAP is stored within warehouses, maintaining a dry and well-ventilated environment to avert moisture absorption until it undergoes processing.

In the processing stage, the RAP undergoes segregation based on its grain size and is subjected to comprehensive composition and quality analysis. In accordance with the assessment of the RAP's characteristics and the intended proportion for mixture integration, appropriate quantities, and qualities of virgin materials are introduced to the equipment. Then, the mixture is formulated according to the equipment's configuration, culminating in a recycled asphalt mixture.

FIGURE 3 – Life cycle of the PSS solution



Within this cycle, a notable challenge arises from the heterogeneous pavement conditions encountered. These conditions encompass a spectrum of factors, such as variations in the thickness of the milling layer, material oxidation levels, inherent moisture content, and the original composition, including binder content, additives, and virgin material properties (MA et al., 2022). Effectively tackling these variations holds significant importance as it ensures the production of uniform and superior-quality asphalt mixtures within the recycling process (ZAUMANIS et al., 2015).

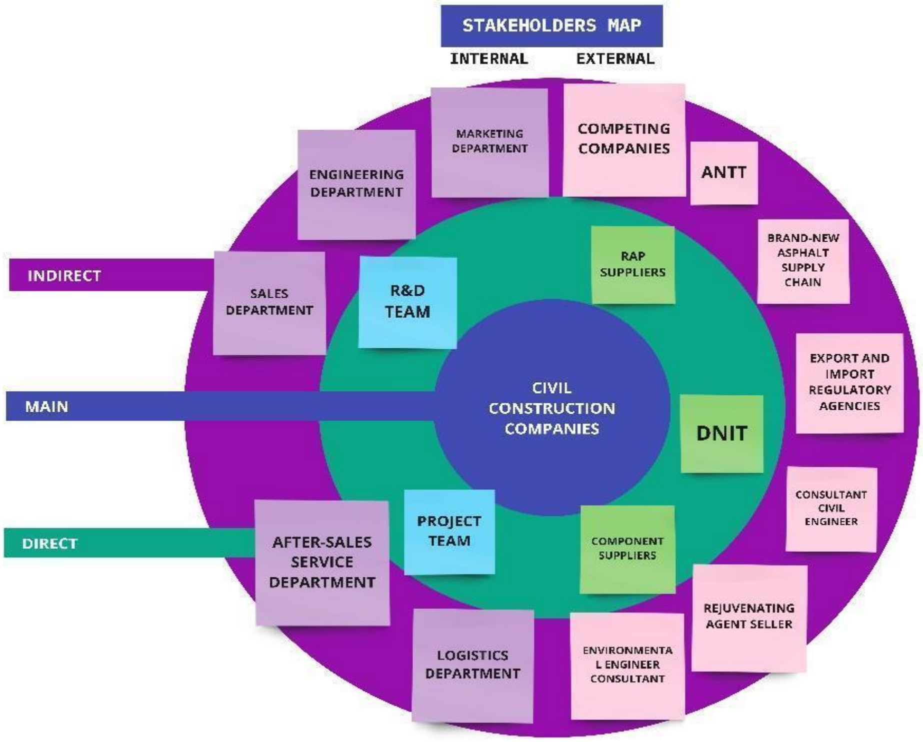
Stakeholders can be categorised based on various criteria, contingent upon the strategic context of the analysis (MILES, 2017a). Following a classification model proposed by Miles (2017b), stakeholders are segregated into direct and indirect categories based on their relational perception and further classified as external or internal based on their organisational affiliations. To identify the stakeholders, we conducted a focus group with Company X. During this interactive session, a collaborative platform (BABOK, 2015) was employed to construct an online onion map. This assessment aimed to evaluate the stakeholders' interaction with the company of the case study and ultimately contribute to the value of the PSS solution from the stakeholders' standpoint.

Within the onion map framework, the blue circle's central point (or core) designates the principal stakeholder or critical actor. Direct stakeholders are positioned near the centre within the inner (green) circle, while indirect stakeholders are portrayed on the outer periphery within the outer (purple) circle.

Our analysis indicates that civil construction companies, including highway concessionaires, contractors, subcontractors, and municipal infrastructure departments, form the primary customer segment. Secondary customers, such as airports, shopping malls, stadiums, supermarkets, and parking lot management/ownership companies, are customers of the primary customers.

Within the context of the PSS solution, internal participants linked to the asphalt plant company, illustrated by lilac post-it notes on the Onion Map (Figure 4), encompass various departmental teams, such as engineering, sales, after-sales, marketing, and logistics. Moreover, project teams and research and development (R&D) units, denoted by blue post-it notes on the Onion Map, are directly connected to the company and exert influence on the PSS solution. External actors on the Onion Map's right side exert an indirect influence on the system without a direct link to the company. These entities are depicted by pink post-it notes and comprise competitors, suppliers within the virgin asphalt supply chain, regulatory bodies for import and export, engineering consultancy firms, suppliers of rejuvenating agents, and the National Land Transportation Agency (ANTT). Conversely, external stakeholders placed closer to the centre of the Onion Map, denoted by green post-it notes, directly impact the PSS solution. This subgroup encompasses component suppliers, RAP suppliers, and the DNIT.

FIGURE 4 – Onion Map of the stakeholder analysis of the proposed PSS



SOURCE: Authors

The next step consisted of the application of the Value Proposition Canvas (VPC) tool. The VPC undergoes two distinct phases (OSTERWALDER et al., 2015). The initial phase focuses on understanding customers by discerning their activities, gains, and challenges. The subsequent phase aims to synchronise products and services with the knowledge acquired in the first phase and identify avenues for generating value. During this latter phase, we formulate advantages and "pain relievers" that can be transformed into product and service proposals. Ultimately, by aligning the perspectives of all stakeholders, a singular value proposition is achieved.

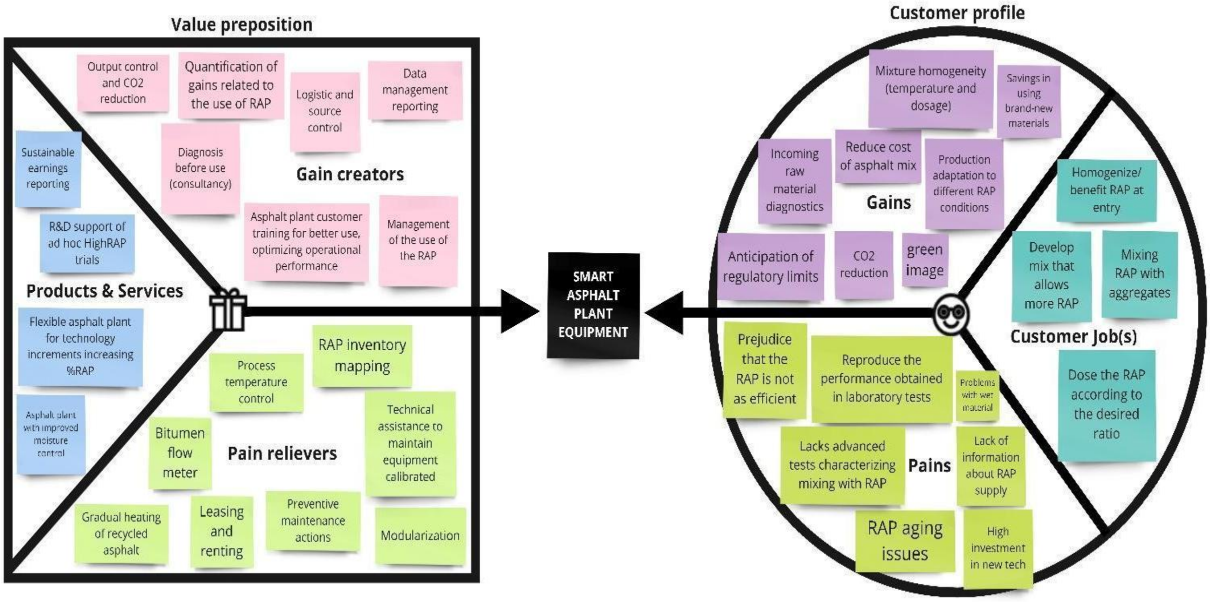
Based on Figure 5, the value proposition (market phase) results revealed several pain relievers and gain creators. The pain relievers that were identified encompass the following: Process temperature monitoring sensors; Gradual and controlled process heating; Bitumen flow metre; Definition of monitoring parameters for predictive maintenance; Technical assistance for equipment calibration; Sieve for separating RAP and aggregate particle sizes; Mapping of RAP availability.

Conversely, the gain creators that were identified encompassed the following: Reports demonstrating the cost savings in production and the amount of recycled material utilised;

Control of the origin of milled material; Enhanced ecological image; Acquisition of carbon credits; and Control of process parameters through smart mechanisms, including emission filters, dosing systems, input particle size sieve for RAP and virgin aggregates, bitumen flow metre, attached drying drum, temperature sensors, and energy consumption sensors.

The proposed offerings encompass a diverse range of products and services strategically designed to highlight the enduring economic, environmental, and social advantages associated with integrating a greater proportion of RAP. These solutions also involve partnerships with academic research laboratories to develop performance tests and conduct analyses on the composition of asphalt mixtures. Furthermore, a specialised dryer has been developed to mitigate the impacts of moisture in RAP. Collectively, these sophisticated resources empower vigilant oversight throughout every phase of the asphalt production process. This comprehensive assembly can be referred to as intelligent equipment for asphalt plants, coalescing into a compelling proposition of value.

FIGURE 5 – Value Proposition Canvas of asphalt plant equipment



SOURCE: Authors

Derived from the insights gleaned through the VPC and subsequent dialogues with the company, we instigated specific adaptations to the business model. This strategic pivot was orchestrated to enhance its alignment with stakeholders' distinct needs and preferences.

The main changes in the business model based on the VPC were to include quality testing in the value proposition, specifying its limitations, and possibilities of offering customers cooperative consulting services in the quality area. Another worthy note is the attention to the requirement of capacity flexibility in order to meet potential future regulatory boundaries. These alignment activities close Phase 0 according to methodology R-PSS.

3.2 ESTABLISHING CUSTOMER-DEMANDED AND TECHNICAL REQUIREMENTS INTEGRATION (PHASE ONE)

Requirements Engineering (RE) stands as a pivotal facet within the realm of system development, as emphasised by Kravari et al. (2020). At its core, RE revolves around the delineation of the objectives set to be realised by the prospective system, as articulated by Lamsweerde (2000). In this regard, our efforts were channelled into crafting intricate specifications, drawing from an in-depth comprehension of the business model and contextual intricacies of the envisioned PSS. Phase 1 of the R-PSS method encompasses a sequence of pivotal actions, encompassing customer requisites' elicitation, categorisation, and prioritisation. Simultaneously, it involves identifying, ranking, and adept management of trade-offs inherent in technical prerequisites. Ultimately, both the customer's and technical exigencies are unambiguously expounded upon during their public dissemination, thus culminating in the conclusion of Phase One.

The stage of requirements elicitation plays a pivotal role in bringing stakeholders' needs and desires to the forefront. To achieve this objective, we engaged in semi-structured in-depth interviews, the framework of which is illustrated in Table 1. A total of 12 stakeholders were actively involved in these interviews, with the average duration of each interview spanning approximately 40 minutes. In accordance with the insights of Hull, Jackson & Dick (2011), the process of eliciting requirements is far from trivial: respondents often articulate their sentiments in their own unique manner, necessitating a degree of interpretation. In order to streamline the endeavour of capturing stakeholders' requisites, these scholars recommend a vital approach – the unambiguous definition of the scope of the envisioned system. This critical element was addressed during Phase Zero through the utilisation of tools such as the Project Charter and the Lean Canvas.

TABLE 1 – SEMI-STRUCTURED INTERVIEW SCRIPT

Introduction: Could you provide a brief overview of your background, including your professional journey, work experience, and educational background?
General Questions: How does the integration of RAP impact your decision-making process when acquiring new equipment for asphalt production? What advantages do you perceive in utilising technology that allows for more RAP reuse? In cases where you engage RAP suppliers, how do you go about their selection?
Specific Questions: What attributes should asphalt plant equipment possess to ensure effective utilisation of RAP? Could you outline the essential functionalities required for this equipment?
Closing: What do you see regarding the future of asphalt mixtures? Is there anything we did not ask that you think is important to mention or that you would like to add?

SOURCE: Authors

Based on the interview insights, we methodically documented the assertions that outlined the capabilities, traits, and constraints crucial for the envisioned PSS solution. Following this, we initiated translating these statements into actionable requirements as demanded by the customers. These customer-driven prerequisites were thoughtfully organised into five distinct categories known as high-level requirements. In accordance with the definition provided by Aurum & Wohlin (2005), these high-level requirements encapsulate overarching and generalised expressions of desired outcomes or functionalities. The summarisation of these categorisations is conveniently presented in Table 2.

An online survey was conducted to gauge the prioritisation of high-level requirements and their corresponding implemented requirements (customer-demanded requisites). The survey encompassed three distinct sets of questions. In the initial set, respondents' suitability was assessed by inquiring about their stakeholders' role and familiarity with RAP.

Subsequently, the second set of questions delved into the respondents' viewpoints regarding the significance of the deployed requirements. Evaluation of their importance was based on the scale advocated by Ulrich et al. (2020), where the assigned scores correspond to the following interpretations: (1) Feature is undesirable, I would not consider a product with this feature; (2) Feature is not important, but I would not mind having it; (3) Feature would be nice to have, but is not necessary; (4) Feature is highly desirable, but I would consider a product without it; (5) Feature is critical. I would not consider a product without this feature.

In the last (and third) set of questions, participants were queried about their demographic particulars, including factors such as age, city of residence, and years of professional experience. This comprehensive data was collected from nineteen RAP specialists who responded to the questionnaire. The availability of this dataset facilitated a hierarchical analysis of both high-level and customer-demanded requirements. Within this context, the Quality Function Deployment (QFD) tool was employed to systematically assess and prioritise customer requirements. QFD is recognised for its methodical approach, which aligns with customers' requirements and their associated significance rankings (AKAO & MAZUR, 2003).

TABLE 2 – Requirements categorisation and prioritisation

Requirements categorisation		Requirements prioritisation				
High-level requirements	**Deployed requirements demanded by the customer**	**Weigh**	**Weigh %**	**Geometric mean**	**DQi**	**DQi***
HARDWARE TECHNOLOGY	C4.2. Ensuring equipment resilience to input moisture variations	3.32	25.16%	4.27	6.08	
	C4.5. Robustness of dosers to particle size variation			4.03	5.74	
	C4.1. Offering equipment modularisation			3.31	4.71	
	C4.3. Reducing abrasion of asphalt plant parts due to RAP			3.14	4.47	
	C4.4. Preferring gravimetric asphalt plants for RAP incorporation			2.92	4.15	
SOFTWARE TECHNOLOGY	C5.4. Adjusting asphalt mixture formula in operation	2.87	21.75%	4.38	5.69	
	C5.1. Measuring gains from RAP incorporation			4.31	5.60	
	C5.2. Monitoring RAP supply availability			4.24	5.51	
	C5.3. Offering predictive maintenance of the equipment			3.80	4.94	
SUSTAINABILITY	C1.2. RAP binder that can be reused	2.64	20.04%	4.47	3.94	
	C1.4. Reduction of greenhouse gas emissions			3.95	3.48	
	C1.3. Reduction of energy consumption			3.86	3.41	
	C1.1. A system with a more sustainable rejuvenating agent			3.57	3.15	
	C1.6. Obtaining carbon credits			3.49	3.07	
	C1.5. Recognised certification (green seal mark)			3.39	2.99	
OUTPUT QUALITY	C3.1. Providing performance tests to guarantee quality	2.19	16.60%	4.31	2.96	
	C3.5. Making quality tests economically accessible			4.31	3.00	
	C3.6. Ensuring quality equivalent to laboratory results			4.24	2.96	
	C3.2. Offering cooperative consultancy between contractor and concessionaire			3.82	2.67	
	C3.4. Providing certified performance tests			3.65	2.54	
	C3.3. Offering cooperative consultancy between contractor and plant manufacturer			3.48	2.42	
OPERATIONAL PERFORMANCE	C2.1. Ensuring mixture homogeneity	2.17	16.47%	4.82	3.52	
	C2.3. Ensuring temperature homogeneity			4.82	3.52	
	C2.4. Ensuring performance in the face of material moisture variations			4.67	3.41	
	C2.2. Ability to use the mixture in the wearing course (Noble Destination)			4.37	3.20	
	C2.5. Controlling oxidation of the milled material			3.84	3.97	

SOURCE: Authors

This tool serves as a vehicle for systematically bridging customer demands with the development process.

Derived from the assessed ratings assigned to each requirement, we adjusted the weights attributed to the demanded quality items (DQi) by employing the principles inherent in Quality Function Deployment (QFD). To execute this, a dual weighting process was applied to each requirement, incorporating two distinct business model factors: competitiveness assessment (Ci) and strategic assessment (Si).

Regarding the assessment of demanded quality items' competitiveness (Ci), Company X assigned a uniform score of 1 point to all items. This score signifies equivalence to the competition, given that geographic competitors maintain an even playing field in terms of RAP application. The assessment of competitiveness scores follows the structure introduced by Callegaro et al. (2016), where the assigned scores correspond to the subsequent categories: (0.5) Above the competition, (1.0) Similar to the competition, (1.5) Below the competition, and (2.0) Far below the competition.

Conversely, the strategic evaluation of the demanded quality items (Si) factors in their relevance to the company's overarching business goals. The evaluation was conducted based on the scoring methodology established by Callegaro et al. (2016), wherein the following scale was employed: (0.5) denotes low importance, (1.0) signifies medium importance, (1.5) represents high importance, and (2.0) indicates very high importance. The majority of items were allocated a score of 1 point, signifying a moderate level of importance. However, oxidation management in the milled material (C2.5) was assigned a score of 2, underscoring its heightened significance compared to other requirements. The computations pertaining to the customer-demanded quality items were executed through the utilisation of Equations (1) and (2), following the guidelines laid out in work by Callegaro et al. (2016).

$$DQ_i = W_i \times \frac{G_c}{\sum_{i=1}^{n} G_c} \times 100 \quad (1)$$

$$DQ_i^* = ID_i \times \sqrt{C_i} \times \sqrt{S_i} \quad (2)$$

Where, DQ_iindex of the importance of the demanded quality item; The weight (W_i) of the high-level requirement i is determined by calculating the geometric mean assigned to its category concerning the total sum of weights assigned to all high-level categories, where G_c = geometric mean of the items belonging to a certain category; DQ_i^* corrected index of the importance of the demanded quality item; S_i = strategic evaluation of the demanded quality item; and C_i = competitiveness assessment of the demanded quality item (*benchmarking*).

The content provides an overview of the customer-demanded deployed requirements. As an illustration, for the specific requirement denoted as C4.2, employing Equation (1) yielded a value of $DQ_i = 6.08$; $C_{4.2}$ and $S_{4.2}$ received a score of 1, so that by Equation (2) results = 6.08. Aside from $C_{2.5}$, which received a score of $S_{2.5} = 2$ and consequently led to DQ_i*= 5.62, all other results in DQ_i are identical to those in DQ_i* since each S_i and C_i was assigned a score of 1.

The arrangement follows a formal structure, with priority categories prominently placed at the top. Within each category, requirements are systematically organised in descending order of importance, with the most critical ones listed first and the less significant ones following suit. Afterwards, drawing from the customer-demanded requirements, a set of technical requirements was formulated. This framework permits the evaluation of how well these technical requirements align with customer demands through the application of measurable indicators. This approach lends itself to effective goal management, focusing on continuous improvement.

For every technical requirement identified, a specification was meticulously defined. This specification represents the targeted quantitative value that the process should attain. The fulfilment of a given technical requirement's specification was anticipated to correlate with the satisfaction of the corresponding customer requirement. This principle aligns with the insights put forth by Royer (2009).

Subsequently, we presented the refined version to the company's decision-makers for their assessment and approval. In the context of analysing technical requirements, it is important to verify their interdependence relationship and their impact on customer-demanded requirements in order to prioritise those that may have a more significant impact on generating customer value.

To facilitate this, we formulated a Quality Function Deployment (QFD) approach that establishes a linkage between customer-demanded requirements and technical requirements, as depicted in Figure 6a. The prioritised technical requirements were meticulously matched with the corresponding customer-demanded requirements and their respective specifications.

Although the analysis incorporated all customer-demanded requirements and related technical requirements, for the sake of clarity, only five are presented in Figure 6a. The values showcased were derived from comprehensive calculations encompassing all customer-demand and technical requirements.

Within the QFD quality matrix, drawing inspiration from the works of Callegaro et al. (2016), and Akao (1990), technical requirements that exerted a substantial influence on specific customer-demanded requirement items were attributed a score of 9. Those with a moderate impact received a score of 3, and those with a minimal impact were assigned a score of 1. In effect, this allowed us to pinpoint the technical requirements that held the utmost significance in relation to customer-demanded requirements. The technical requirements were subjected to additional weighting to further refine the evaluation. This entailed assessing two factors: the difficulty of acting on the technical requirements (Dj) and the competitiveness assessment of the technical requirements (Cj).

The evaluation of the difficulty associated with addressing technical requirements (Dj) gauges the intricacy involved in modifying the specifications of said technical requirements. The scale utilised for this assessment draws from the framework established by Callegaro et al. (2016), encompassing the following gradations: (0.5) Very difficult; (1.0) Difficult; (1.5) Moderate; (2.0) Easy. This assessment framework aids in determining the feasibility of effecting changes to technical requirements while accounting for their potential complexities.

Concurrently, the competitiveness analysis of the technical requirements (Cj) hinges on benchmarking these requirements against those of competitors. This evaluation method involves comparing the organisation's product with that of rivals, with a specific focus on the technical requirements. The evaluation scale used for this purpose is rooted in the work of Callegaro et al. (2016) and comprises the subsequent ratings: (0.5) Above competition; (1.0) Similar to competition; (1.5) Below competition; (2.0) Far below competition. This assessment aids in contextualising the organisation's performance and competitiveness concerning technical requirements within the industry landscape.

Subsequently, we conducted an additional focused discussion, this time involving the R&D team of the asphalt plant company. The goal of this session was to validate and solidify the connections between customer-demanded requirements and technical requirements. During this collaborative effort, the R&D team's expertise was harnessed to enhance the accuracy of these relationships.

Throughout this process, a technical requirement emerged pertaining to the reduction of greenhouse gas emissions. However, this pursuit was deemed intricate due to the necessity of continually sourcing and transporting RAP, which could often originate from distant locations. Conversely, a pronounced focus was directed toward a technical requirement involving the minimisation of asphalt oxidation during the milling process. This emphasis stemmed from its direct influence on the quality of the recycled material.

The prioritisation of technical requirements was established through the application of Equations (3) and (4), following the methodology outlined in the work of Callegaro et al. (2016). Employing this method facilitated a methodical and impartial evaluation of the significance of technical requirements while simultaneously ensuring their harmonisation with the broader objectives of the project.

$$TQ_j = \sum_{i=1}^{n} DQ_i^* \times RD_{ij} \quad (3)$$

$$TQ_j^* = TQ_j \times \sqrt{D_j} \times \sqrt{C_j} \quad (4)$$

Where: TQ_j= index of the importance of the technical requirement item, DQ_i^*= index of the importance of the corrected demanded quality item, RD_{ij}= relationship of the demanded quality with the technical requirement item, TQ_j^*= index of the importance of the corrected technical requirement item, D_j= assessment of the difficulty of acting on the technical requirement item and C_j= competitiveness assessment of the technical requirement item.

In contrast, other technical requirements, such as "Maximum moisture content of RAP input without significant change in quality tests" and "% reduction in overall asphalt manufacturing costs" were deemed to wield a more pronounced impact across a broader spectrum of customer-demanded requirements. These requirements, marked by a high importance index, were consequently prioritised in subsequent deployment phases. This strategic allocation is visualised in Figure 6d, reflecting the strategic emphasis placed on these high-impact technical requirements moving forward.

The process of prioritising technical requirements gains further precision by scrutinising trade-offs among them. This examination seeks to uncover potential supportive or conflicting relationships among the proposed PSS's technical requirements. The Matrix of Trade-offs, formulated by QFD (AKAO, 1990), is employed to identify these relationships. This matrix is visually presented in Figure 6b. Relationships characterised by support are denoted by positive symbols (+), signifying their positive correlation, while conflicting relationships are symbolised by negative symbols (-), indicating their contrasting nature. This insightful analysis illuminates the intricate interactions among technical requirements, informing the strategic decision-making process and ensuring a holistic understanding of their implications.

One of the positive relationships identified involves the connection between "% variation in milled asphalt (physical and chemical) in different samples within a batch" and "Maximum temperature reached in the process at any point." This relationship stems from the equipment's mixing capacity throughout the process, aimed at counterbalancing the heterogeneity present in RAP as opposed to virgin raw material.

Both of these technical requirements hold significance in addressing the high-level requirement of "Hardware Technology". Consequently, it is advised to prioritise both these requirements. Their complementary nature reinforces the need for a well-balanced approach that effectively addresses the complexities introduced by the variable nature of RAP materials.

A notable negative relationship is evident between the requirement "Maximum moisture content of RAP input without significant change in quality tests" and "Acceptable % variation in asphalt stability at critical moisture." This relationship underscores the trade-off between the potential to accommodate higher moisture content in the RAP input and the inherent difficulties of sustaining process stability when dealing with elevated initial moisture levels. This dynamic aligns with the Brazilian regulation DNIT 033/2021-ES specifications document in Annex C, Table C1 (DNIT, 2021b).

Given this trade-off, it appears that exploring alternatives might be more favourable. Focusing efforts on refining process quality right from the outset could be a more compelling avenue, as it can mitigate the challenges arising from elevated moisture content and simultaneously enhance overall process stability. This evaluation demonstrates the need for a balanced consideration of various factors to make a judicious decision.

FIGURE 6 – QFD steps

Customer requirements	Maximum acceptable RAP inlet moisture (%)	Direct reduction (%) in overall asphalt manufacturing costs	Maximum % of binder used in the mixture	Maximum temperature reached in the process at any point	% variation of quality parameters from laboratory to plant	...	DQi (Weight of customer requirement)	Ci (Competitiveness assessment)	Si (Strategic assessment)	DQi*
C4.2. Ensuring equipment resilience to input moisture variations	9			9	1					6.08
C5.1. Measuring gains due to RAP incorporation		9	3		3					5.60
C1.2. Reusing RAP binder		3	9	3						3.94
C2.3. Ensuring temperature homogeneity			3	9						3.52
C3.6. Ensuring quality equivalent to laboratory results	1	1		1	9					2.96
...										
SPECIFICATIONS	8%	5%	4%	180°C	5%					
TQj	Weight of technical requirement									
Dj	Difficulty on acting									
Cj	Competitiveness analysis									
TQj*	55.09	60.08	52.09	56.48	47.11					

a) QFD PSS quality matrix

Technical requirements	Maximum acceptable RAP inlet moisture (%)	Direct reduction (%) in overall asphalt manufacturing costs	Maximum % of binder used in the mixture	Maximum temperature reached in the process at any point	% variation of quality parameters from laboratory to plant	...
Maximum acceptable RAP inlet moisture (%)	0			-	+	
Direct reduction (%) in overall asphalt manufacturing costs		0	+			
Maximum % of binder used in the mixture			0			
Maximum temperature reached in the process at any point				0	+	
% variation of quality parameters from laboratory to plant					0	
...						0

b) QFD PSS quality matrix trade-offs

Prioritised demanded requirements	Prioritised technical requirements	TQj*	Process steps
C5.1. Measuring gains from RAP incorporation	Direct reduction (%) in overall asphalt manufacturing costs	60.08	Analyze reduction of use of virgin RMs
C1.4. Reducing greenhouse gas emissions	% reduction of greenhouse gases	57.81	Designing monitoring software
C2.1. Ensuring mix homogeneity	% physical variation in mix in different samples within a batch	57.05	Control the composition of the mixture in process
C2.3. Ensuring temperature homogeneity	Maximum temperature reached in the process at any point	56.48	Monitor the correct use of equipment
C4.2. Ensuring equipment resilience to input moisture variations	Maximum acceptable RAP inlet moisture (%)	55.09	Control mix moisture
C2.5. Controlling oxidation of the milled material	Reduction (%) of milled material oxidation	53.71	Control milling quality
C1.2. Reusing RAP binder	Maximum % of binder used in the mixture	52.99	Define ideal mixture composition
C3.6. Ensure quality equivalent to laboratory results	% variation of quality parameters from laboratory to plant	47.11	Provide supplemental mix quality testing
C2.4. Ensuring performance in face of material moisture variations	% stability variation in asphalt at critical humidity	44.77	Designing subsystems
C3.5. Making quality tests economically accessible	% customer cost reduction in quality tests	41.01	Investing in quality and performance assays research

c) QFD process deployment

Process steps	Direct reduction (%) in overall asphalt manufacturing costs	Maximum temperature reached in the process at any point	Maximum acceptable RAP inlet moisture (%)	Maximum % of binder used in the mixture	% variation of quality parameters from laboratory to plant	...	IPRi (Process weights)	IDi (Implementation difficulty)	ITi (Implementation time)	IPRi*
Technical requirement priorities (TQj*)	60.08	56.48	55.09	52.99	47.11					
Analyze reduction of use of virgin RMs	9			1						100.67
Monitor the correct use of equipment	3	9	1		1					176.36
Control mix moisture		9	9	3	3					239.61
Define ideal mixture composition	3	9	9	9	3					367.19
Provide supplemental mix quality testing	1		3	9	9					201.92
...										

d) QFD process matrix

SOURCE: Authors

To summarise, we conducted a qualitative trade-off matrix analysis through a focus group collaboration with the asphalt plant company. The objective was to verify if any prioritised technical requirements presented substantial conflicting relationships that could impede development. Fortunately, the identified trade-offs did not pose obstacles that would hinder the project's advancement. This validation paved the way for proceeding with the publication of the requirements.

In the concluding stage of Phase One, which entails a meticulous examination of the requirements, we obtained approval through the endorsement of pivotal decision-makers involved in the future development of the PSS. This pivotal step signifies the culmination of a comprehensive assessment process, ensuring that the requirements align with project objectives and are ready to drive the subsequent developmental phases.

3.3 INTEGRATING PSS BY ANALYSING CONFLICTING RELATIONSHIPS, DEPLOYING, AND IDENTIFYING CRITICAL PROCESSES (PHASE TWO)

Phase Two involves the integration of the PSS solution by conducting a thorough assessment of conflicting relationships within its processes. This is followed by the deployment and prioritisation analysis of the processes comprising the PSS solution. This phase facilitates a clearer visualisation of the system's activities and enables the identification of avenues for enhancing both products and services. The primary objective is to ensure the effective alignment of technical requirements with customer demands, thereby ensuring a cohesive fulfilment of project objectives.

Again, in a focus group with the R&D team of the asphalt plant company, the analysis of the PSS processes and their conflicting relationships pointed out that controlling oxidation in the milling process is highly important for the PSS quality, contributing to process reliability and flexibility. Furthermore, it is necessary to define the extent to which the services provided by the asphalt plant manufacturer can impact the quality of the milling process. The process deployment - see Figure 6c - is essential for a better visualisation of the system and for taking into account its conflicting relationships.

We devised a process matrix to pinpoint critical processes within the system by adopting the QFD approach, as depicted in Figure 6d. We specifically selected the key processes associated with the prioritised technical requirements. In this matrix, we assigned a weight of 9 to signify robust relationships between process steps and the prioritised technical requirements. A weight of 3 was designated for relationships of moderate strength, and a weight of 1 for relationships of weaker significance. This assignment allowed us to calculate the IPRi, denoting the index of the importance of the process item.

To refine the evaluation, the asphalt plant manufacturer evaluated these relationships from the lens of two criteria: "Implementation Difficulty (IDi)" and "Implementation Time (ITi)". This assessment yielded the IPRi*, representing the corrected importance index of the process item, a concept analogous to the methodology introduced by Callegaro et al. (2016). The calculation procedure for these indexes adheres to a framework akin to that employed for the QFD quality matrix, ensuring a systematic and coherent evaluation process.

Among the array of critical processes identified, the "Define Ideal Mixture Composition" process emerges as a notable standout. This process holds the distinction of being recognised as a pivotal point of contribution to sustainability, as evidenced in Figure 7 (Product Service Blueprint). Moreover, it is intrinsically linked to seven prioritised technical requirements. Thus, this strategic process plays a central role in shaping the proposed solution and guiding its development.

Equally vital are the critical processes "Provide Supplementary Quality Tests for the Mixture" and "Invest in Quality/Performance Testing Research." These processes collectively underpin the foundation of the proposed solution. Conversely, the critical processes "Design Subsystems", "Control Mix Moisture" and "Design Monitoring Software" collectively formulate a secondary strategy that integrates the proposed solution seamlessly within the project scope. On the other hand, the processes "Monitor Correct Equipment Usage", "Control Quality of the Milled Material" and "Analyse Reduction of Use of Virgin Raw Materials" hold relatively lesser significance within the current company context.

This stage's completion involved the meticulous identification of relationships and overlaps between processes, coupled with their intricate impact on technical requirements. Anticipating potential shifts in the market landscape, the Product Service Blueprint and the process matrix may require reassessment to devise new strategies that align with evolving market dynamics. This flexibility is essential to ensure the solution remains adaptable to changing circumstances while staying aligned with overarching project objectives.

To operationalise the deployment of the PSS and effectively deliver the prioritised technical requirements in accordance with the established value proposition, we harnessed the Product-Service Blueprint tool (GEUM & PARK, 2011). This tool served as the foundation for translating the PSS concept into tangible processes. The blueprint delineates three distinct areas:

- Product Area: This domain is subdivided into the customer product-use processes and the company product-management processes. This division delineates the product's journey from the customer's perspective and its subsequent management by the company.

- Service Area: It encompasses front-office and back-office services. The front-office service pertains to the visible interactions and services provided to customers, while the back-office service involves internal processes that support the overall service provision.

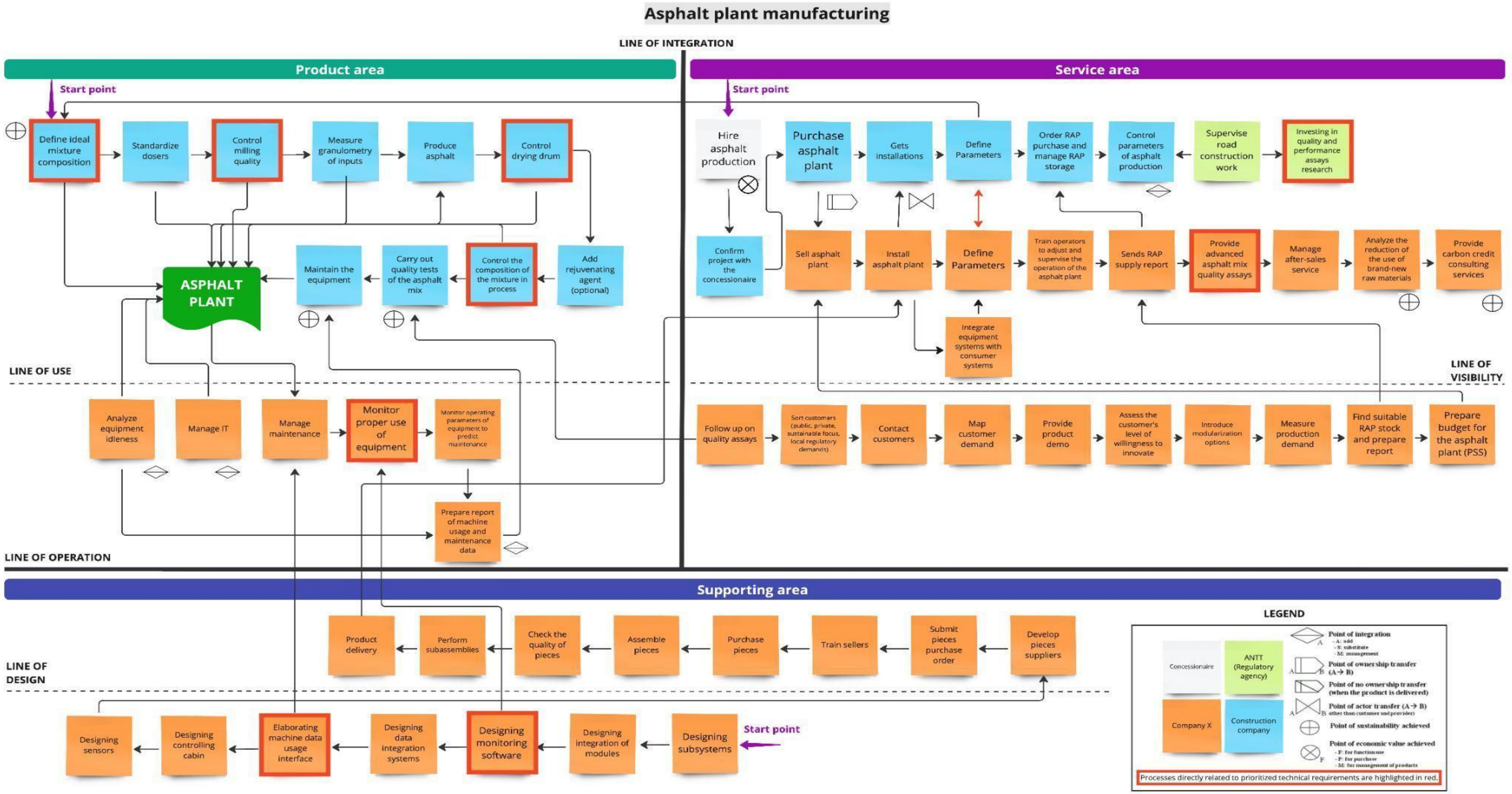
- Support Area: This area is further categorised into solution design and implementation/manufacturing. It encompasses the strategic design of the solution as well as its practical realisation and manufacturing.

Given the nature of the PSS offering (TUKKER, 2004), where products and services are intricately entwined, it is natural for activities within these different areas to be interdependent. This cohesive interrelation fosters a seamless and holistic delivery of the PSS solution, ensuring that both technical requirements and customer expectations are adequately addressed across the entire spectrum of the offering.

The system reveals insightful observations: its series of actions commence with the design and subsequent manufacturing of the asphalt plant, a pivotal cornerstone within the prevailing product-oriented PSS structure. During the design phase, the strategic incorporation of requirements aligned with the operational imperatives of the asphalt plant assumes pivotal significance. To illustrate, ensuring the efficient monitoring of equipment usage demands a seamless alignment of monitoring software design with the specified technical prerequisites.

Another notable facet revolves around the process of installing asphalt plants, contingent upon a complex network of essential back-office activities that underpin equipment sales. This installation juncture serves as a catalyst, initiating a cascade of supplementary services and novel possibilities. These possibilities include avenues for extending supplementary or advanced quality tests for asphalt mixtures and exploring the potential utilisation of recycled raw materials in asphalt production.

FIGURE 7 – Product-Service Blueprint of the proposed PSS



SOURCE: Authors

This intricate interplay aptly underscores the dynamic nature of the system, where synchronised actions synergise to bestow heightened value, cater to diverse customer demands, and open up fresh realms of service exploration.

The process of monitoring raw materials both before their entry into the transformation process and consistently throughout the process serves as a catalyst for elevating the production process's reliability and bolstering the organisation's operational performance. This underlines the pivotal role of managing parameters the PSS solution delivers, making it a crucial component in system design. As a result, the execution of processes directly linked to the prioritised technical requirements offers a more comprehensive insight into their influence on the system. This deeper understanding aids in identifying critical processes, which are highlighted in red to emphasize their significance.

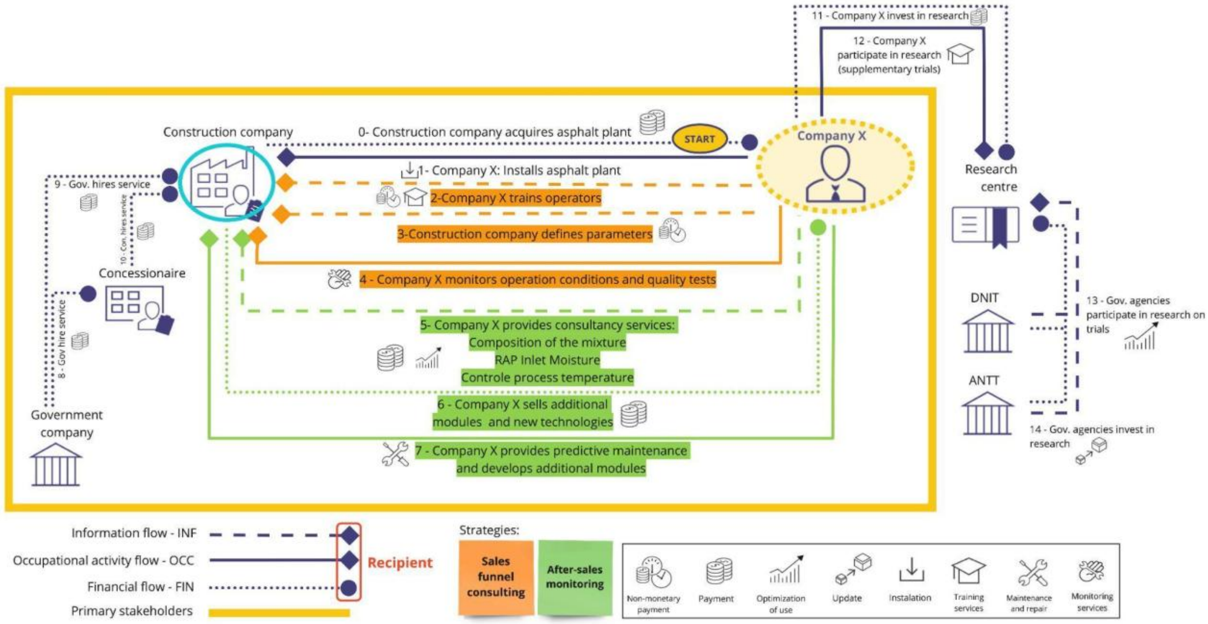
3.4 DESIGNING AND VALIDATING THE SOLUTION - BY PORTRAYING FLOWS AND THE CONCEPT - AND ASSESSING ITS CONTRIBUTION TO SUSTAINABILITY (PHASE THREE)

Phase 3 consists of three steps. In the first step, we illustrate the interaction pathways using a stakeholder-oriented model known as the System Map (VEZZOLI et al., 2014). This instrument aids in visualising the value chain's framework, going beyond just identifying stakeholder interactions and instead emphasising the informational, financial, and labour flows (VEZZOLI et al., 2014).

Figure 8, the system map, illustrates the socio-economic actors participating in the system, categorised into two groups: primary and secondary actors. Primary actors encompass governmental companies, concessionaires, and construction firms, which are the key entities related to Company X, the subject of our study. Among these, construction companies bear the greatest impact when adopting new technology, as they must align with customer demands, often requiring early adoption of new technologies and staff training for new processes.

Additionally, the system map highlights distinctive flows related to consultancy in the sales funnel (depicted by orange lines) and after-sales monitoring (illustrated by green lines). It's important to note that while these flows may also occur for other actors within the system, they hold particular significance based on interviews and subsequent validation with Company X's managers.

FIGURE 8 – System map of the proposed solution PSS



SOURCE: Authors

Secondary actors play a supporting role in governmental companies, concessionaires, and construction firms. These secondary actors include research centres engaged in scientific studies encompassing various physical-chemical, geological, and meteorological aspects. Furthermore, the DNIT plays a vital role in implementing terrestrial and waterway transportation infrastructure policies, contributing to the nation's sustainable development through technical studies related to transportation and road systems' maintenance, expansion, construction, and supervision.

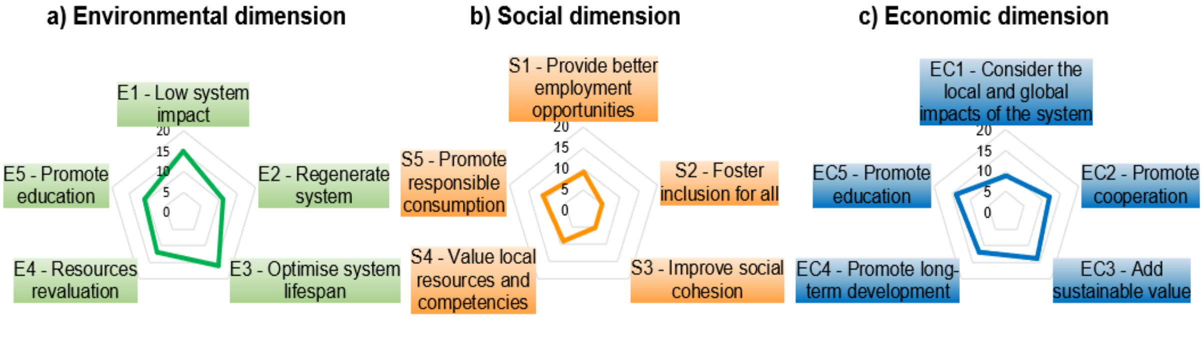
Another identified actor is the ANTT, which conducts studies on traffic and transportation service demand. It also focuses on establishing standards and technical regulations for infrastructure exploitation and the provision of land transportation services. ANTT acts as a regulator, overseeing contractual clauses for service provision permits and infrastructure exploitation concessions. In summary, secondary actors may not directly influence the sustainable PSS proposed but contribute significantly to its realisation.

In the second step of Phase 3, for developing the PSS concept, we utilised a standardised form created by the Learning Network on Sustainability (LENS), which is accessible through the Miro(R) link provided in the Supplementary Data. The essential information of the solution is condensed into a statement, offering a concise overview of the proposed sustainable PSS. In simpler terms, the proposed PSS entails the establishment of an asphalt plant with an increased proportion of RAP utilisation, resulting in sustainability benefits by repurposing a by-product, reducing the need for virgin materials, fostering partnerships with local suppliers, and ultimately enhancing economic efficiency. Keeping in mind the assessed requirements, the primary principles are to maintain the integrity of hardware technology while making it more robust and advancing software technology to include comprehensive monitoring of previously untracked parameters. Consequently, the PSS solution must not only deliver materials and digital metrics enhancements but also provide a service catalogue for optimising the newly integrated advantages within the sustainable PSS proposal.

In the third step of Phase 3, pertaining to the validation of the PSS, this process involved multiple interactions with the company. Additionally, validation for the sustainable PSS solution occurred on two fronts: internally, through an evaluation of its contribution to sustainability, and externally, in a workshop presented to key decision-makers for the PSS (Company X managers). During this workshop, we presented the PSS design, highlighting the aspects aligned with sustainability, including requirements and processes, as well as the involving stakeholders.

As for assessing the contribution to sustainability in PSS, we employed an adapted version of the ad hoc tool developed by Silveira et al. (2022). This tool assigns a score to each statement (item) within the categories linked to the dimensions of sustainability - the triple bottom line (WCED, 1987), as depicted in Figure 9. There are a total of five categories, and each one comprises four statements (items) evaluated on a six-point Likert scale: (0) Not Applicable; (1) Strongly Disagree; (2) Partially Disagree; (3) Indifferent; (4) Partially Agree; (5) Strongly Agree.

FIGURE 9 – Assessment of the contribution to sustainability in PSS



SOURCE: Authors

The assessment of the environmental dimension is rooted in the commitment to support the environment by promoting two key aspects: the reduction of environmental risks and the mitigation of environmental impacts resulting from activities involved in the development of the PSS. In light of this, we have identified opportunities to enhance the environmental aspect of the proposed PSS solution under the following categories: E1 - Creating Low Environmental Impact Systems; E2 - Minimising Resource Utilisation in the System; E4 - Extending the Lifespan and Revalorisation of System Resources. For instance, item (a) of E1 had a low score, which reflects an opportunity to improve the use of renewable and clean energy throughout the PSS chain, from suppliers to customer delivery.

Likewise, the assessment of the social dimension is grounded in the commitment to uphold principles that promote social equity in opportunities and responsibilities, as well as respect for individual rights. Several opportunities have been identified to enhance the social aspect of the PSS solution, focusing on the following categories: S2 - Promoting Inclusion for All; S3 - Enhancing Social Cohesion.

These opportunities suggest actions such as involving the entire internal team, as well as an external team, in the oversight of the PSS from its design to manufacturing stages. Additionally, they involve promoting more participatory communication and actively listening to stakeholders.

Finally, the evaluation of the economic dimension is grounded in the commitment to foster economic development and growth, focusing on both the enterprise's economic well-being and stakeholders' economic advancement. In this context, specific categories highlight opportunities to bolster the economic aspect of the proposed PSS solution: EC2 - Promoting Networked Organisations, stimulating cooperation and partnership. Emphasis on (c): Developing distributed flows that facilitate access to resources and expand economic reach; EC5 - Promoting Education for a Sustainable Economy. Emphasis on (b): Enabling capacity-building for an economy focused on promoting the quality of life for all.

These opportunities underscore the importance of fostering cooperation, partnership, and resource accessibility (EC2) as well as enhancing education and capacity-building to support an economy geared towards improving the quality of life for all (EC5). By prioritising these aspects, the economic dimension of the PSS can be enhanced, benefiting both the enterprise and its stakeholders.

4 DISCUSSIONS

Brazil has been distinguished for providing more sustainable initiatives in all industrial sectors. In the construction industry, one notable initiative is the incorporation of RAP into asphalt production. Although there is currently no specified minimum percentage, the incorporation of RAP in asphalt production is legally mandated. To effectively address this requirement, managers and the entire production chain must prepare to embrace this change to enhance sustainable value. This article proposes a sequence of steps that can be replicated in projects that need to plan and manage similar changes. The proposed set of steps contributes to understanding the issue and also involves key stakeholders to become co-authors in driving this transformation.

The studied company aims to achieve differentiators such as providing a product with a more long-lasting life cycle, a more attractive return on investment (ROI) for their customers (which means reducing costs), and an increasing sustainable value, mainly but not limited to, the use of higher percentages of RAP in asphalt production. Moreover, the revision of the business model after the application of the VPC tool evidenced an opportunity to innovate the business model.

The utilisation of the VPC tool revealed an opportunity to innovate the business model, leading to its revision. Although a user-oriented solution based on sharing or leasing services was not prioritised in the company's strategic decisions, there is potential for enhancing the company's current product-oriented business model, especially considering the market's maturity level. Shifting towards a more use-oriented or result-oriented PSS solution can offer opportunities for diversification, expand the range of solutions, and address emerging market sectors' needs. Furthermore, this transformation can contribute to greater sustainability and facilitate the industry's transition to a circular economy.

The stakeholders in the pavement industry chain need to be considered when evaluating the proposed solution's potential. Changes in both the physical product (such as enhancing the robustness of the asphalt plant equipment) and services (including guidance on optimised use) are required to meet customer expectations and improve the asphalt production process. However, the life cycle of the PSS solution, which involves various stages like milling pavement to obtain RAP, studying its composition and quality, and producing a recycled asphalt mixture, poses an emergent challenge in the Brazilian context due to the diversity of pavement conditions.

The value proposition of the PSS solution encompasses pain relievers (e.g., process monitoring sensors, technical assistance, and mapping of RAP availability) and gain creators (e.g., cost savings, ecological image, and control of process parameters). It also involves leveraging intelligent resources and establishing partnerships with academic research laboratories.

Nevertheless, there are pertinent limitations to address. These include limited experience in quality assessment tests for asphalt mixtures with RAP, lack of awareness that performance can match or surpass that of entirely virgin asphalt, and a lack of regulations regarding sustainable asphalt. Meeting criteria related to compaction level, density, uniformity, water damage susceptibility, longevity, and resilience modulus, as highlighted by Tarsi et al. (2020) is essential. Additionally, logistical expenses, available production space, time constraints, a range of quality assessments, as well as concerns about water pollution and retention within the asphalt, pose limiting factors.

In the context of a product-oriented PSS system, such as the one analysed in this study, the design and manufacturing of the asphalt plant play a central role. It's crucial to incorporate requirements aligned with plant operations to address technical needs and enable effective monitoring. The installation process of the plant also presents opportunities for ancillary services, such as quality tests and analysis of recycled materials, which enhance monitoring and improve reliability and operational performance. Establishing control parameters through a PSS solution is crucial during the system's design phase.

Above all, this approach exemplified the integration of Circular Economy principles (resource optimisation by recycling) and PSS design. This integration is recognised as a means to enact the Circular Economy (TUKKER, 2015), aiming to reduce resource consumption while promoting economic growth. Whereas Fernandes et al.'s (2020) systematic review highlights the fragmented state of research on Circular and PSS value propositions, notable studies such as Tinoco et al. (2023), Sastre et al. (2019) and Antikainen et al. (2015) have successfully combined Circular Economy and PSS, offering valuable insights.

It is essential to emphasise that incorporating Circular Economy principles at the early stages of product and service development enhances the feasibility of implementing sustainable solutions. By doing so, changes to products or services can be more effectively implemented, as alterations become increasingly challenging during the later stages (BOCKEN et al., 2016).

In conclusion, the utilisation of the R-PSS method is in line with sustainable design thinking. Its comprehensive approach surpasses initial design considerations by establishing value requirements for stakeholders and designing crucial processes to generate and deliver sustainable value throughout the study, encompassing the entire life cycle of asphalt production.

As a limitation of our study, we did not consider a disruptive business model such as leasing or renting asphalt plants, which may be less feasible for a later-industrialised country like Brazil, especially in the pavement sector. Furthermore, we did not address a mechanism for selecting component materials for asphalt plant equipment, neglecting factors such as recyclability and ease of disassembly, which are crucial from a sustainability standpoint, facilitating future recycling or reuse of components.

5 CONCLUSIONS

The objective of this paper aimed to introduce a sustainable solution that enhances the reuse of recycled asphalt within the Brazilian asphalt plant manufacturing industry by utilising the PSS business model. To do so, we used the R-PSS method (ECHEVESTE et al., 2020). Through this approach, we developed a PSS solution that enables the incorporation of a higher percentage of RAP in asphalt production, leading to sustainability gains such as reduced consumption of virgin materials, the establishment of partnerships with local suppliers, and improved economic efficiency.

On top of that, among environmental benefits are circular processes, as a fundamental principle of the R-PSS method (ECHEVESTE et al., 2020), which are rooted in circular business models that embrace the entire value chain from the outset, beginning with the concept design phase of change management projects (business model approach).

To compare with current and next-generation technology, we actively incorporated the requirements and demands of stakeholders. Several aspects were considered in this process, including the quality of the recycled asphalt material, the desired percentage of recycled content, and the performance characteristics of the resulting asphalt mixture. Additionally, designing equipment with modularity and ease of maintenance was deemed crucial for ensuring its longevity. While an effective solution is supported by a robust long-standing hardware technology, the software technology is prone to continue evolving for accurate monitoring purposes.

The proposed PSS was evaluated for sustainability across the three dimensions of the triple bottom-line theory: environmental, social, and economic. There are various opportunities to enhance the environmental pillar, such as reducing environmental risks and minimising resource consumption. Regarding the social pillar, opportunities lie in promoting inclusion and social cohesion. Lastly, the economic pillar can be strengthened by fostering cooperation and partnership and providing education for a sustainable economy.

Building upon our findings, we suggest expanding research avenues to delve into profit analysis, specifically focusing on organisations seeking Environmental, Social, and Governance (ESG) principles aligned with the triple bottom line theory. Furthermore, future studies can explore the specific requirements for a use-oriented or result-oriented PSS solution within the context of the asphalt plant industry, examining the stakeholders' roles in these novel solutions and their contribution to generating sustainable value in promoting the Circular Economy.

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