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A Cost-Engineering Method for Product-Service Systems based on Stochastic Process Modelling: Bergamo's Bike-Sharing PSS

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Abstract

Cost-determination in Product-Service Systems (PSS) presents a broad set of impacts across managerial and design decision-making processes. Most of the effort within PSS-costing literature is focused mainly on the development of techniques that address challenges regarding data availability, lifecycle representation, and uncertainty modelling. Less effort concentrates on the understanding of the PSS-cost nature and its differentiation from the traditional perspective of product-cost and service-cost. In that sense, the purpose of the paper is to provide a description of the PSS-cost nature, and construct a Cost-Engineering method aligned to such definition. This paper proposes a systems thinking approach in which the PSS-cost is observed as an emergent attribute that the PSS, as a complex system, exhibits when is operating. In order to capture the proposed PSS cost nature as an emergent attribute and derive useful managerial insights, a cost-engineering method based on Stochastic Process modelling, has been devised. The data output of the method represents all PSS-cost unrealized potential outcomes with their associated occurrence probability conditioned by a defined performance or/and functionality level. An empirical case study, the Bergamo's Bike-Sharing PSS, has been carried out in order to visualize the proposed method and its managerial implications.

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Keywords: PSS Cost Engineering; PSS Cost Models; Systems Thinking; Stochastic Process; Discrete Event Simulation; System Cost Uncertainty Analysis.

1. Introduction

Cost, as a numeric indicator, addresses several types of questions and provides relevant information to a variety of stakeholders [1]. Moreover, the process in order to determine such 'cost' (cf. costing) provides relevant insights about the analyzed PSS. In PSS literature, *costing* is mainly used: (a) for sustainability assessment, (b) as a metric of provider value, (c) as a metric of customer affordability, (d) for financial assessment, (e) for transition support into PSS business model, (f) for provider pricing mechanisms, and (g) as input for PSS design [1]. It can be seen that *PSS cost-determination* presents a broad set of impacts across managerial and design decision-making processes; nevertheless, it has been found that PSS literature pays little attention to such matter.

Current *PSS-costing* is based on techniques that can be classified into two main types [2] [3]: high-level and bottom-up techniques. The first type of techniques is based on past projects/contracts outcomes, in which future costs projections are defined by considering the similarities and differences with former projects. Most used techniques of this type are estimation by analogy and by extrapolation. The second type of techniques is based on a highly intensive data collection of individual costs, determined by means of mathematical relationships derived from relevant cost drivers attribute(s). Most used techniques of this second type are activity based costing and parametric methods. The first type of techniques are the most used ones, evidencing that PSS costing literature lacks of true cost-engineering approaches.

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Much of the effort in PSS-costing literature is focused mainly on the development of techniques that address challenges regarding data availability, lifecycle representation, and uncertainty modelling. Nevertheless, much less effort is provided in order to understand the PSS cost nature and differentiate it from the traditional perspective of product-cost and service-cost.

Concretely, it is stated that PSS-costing literature does not provide ontologies that characterize the concept of cost from the PSS implications. Setanni *et al.* [4] states that the distinction between methodology (i.e. ontology) and technique is relevant for the cost determination; in which an ontology *"is concerned with 'thinking about how to think', guiding the intellectual process of choosing concepts and deciding how they might be structured, whilst techniques are well-defined ways of 'going about' a problem"*. The importance of developing *ontologies* for the PSS cost-determination relies on the fact that among several ontologies that describe the same piece of reality, some may entail higher complexity for relevant data determination. Therefore, the development of ontologies must precede PSS cost determination [5]. In that sense, the aim of the paper is to both propose a description for the PSS nature based on Systems Thinking, and to construct a Cost-Engineering Method aligned to such definition.

This research work is structured as follows. Section 2 presents the proposed *ontology* in order to understand the PSS nature from the Systems Thinking perspective. Section 3 describes the proposed PSS Cost-Engineering method applied to the Bergamo´s Bike-Sharing PSS case study. Finally, Section 4 presents conclusions and further research work.

2. Product-Service System (PSS) Nature

It is proposed to acquire a *systems thinking* approach, visualizing the PSS as a complex system, defined as a set of autonomous, interrelated and interdependent components, whose interaction produces a set of outcomes in order to achieve one or more stated purposes. The great complexity of such interaction promotes a nonlinear behavior of the PSS. A linear behavior states that the net outcome caused by two or more stimuli is the sum of the outcomes, which would have been caused by each stimulus individually; this is also known as the superposition principle [6]. The lack of such superposition principle in complex systems explains why such systems exhibit *emergent attributes* that cannot be predicted from the properties of the compounding parts. In that sense, the *PSS-cost* cannot be longer seen from the traditional perspective as an *intrinsic property* of products and services separately, but as an *emergent attribute* of the context in which products or services are designed and delivered [7]. The question that arises at this point is how to model the *PSS behavior?*

2.1. PSS Behavior Representation: Stochastic Process

It is proposed to model the PSS behavior as a *stochastic process* in order to capture the proposed nature. The emergent behavior of a PSS cannot be predicted from the properties of the compounding parts, since it is given by a complex interaction among several random variables characterized by the lack of superposition principle. In such sense, it is possible to observe two completely different and contra-intuitive cost values for the same level of performance in the PSS. A *stochastic process* is a probability model used to describe the evolution of some system represented by a variable whose change is subject to a random variation [8]. One important aspect is its *indeterminacy* characteristic, which states that given the random variation, the process will evolve in many different directions. In that sense, the stochastic process modelling captures the emergent behavior when a set of evolution paths of relevant random variables are collected and patterns are identified. Such patterns can be understood as the observed range of values where random variables are found at a precise moment in time, from which probabilities can be computed.

The proposed PSS operation evolution is described by means of (a) functionality, (b) performance, and (c) cost, which enables to answer questions such as what is the cost prediction for a certain level of PSS functionality delivery? Which is aligned with PSS Cost-Engineering discipline understood *as a set of activities in order to determine/predict the operational cost of a PSS configuration performance-functionality level as well as the awareness of the certainty degree of such determination/prediction* [5].

Since such variables are observed as *emergent attributes* of the PSS, given its *unpredictability* aspect, they must be measured while the PSS is operating (i.e. when the PSS exhibits such attributes). In that sense, simulation techniques play a fundamental role in PSS cost-determination. Simulation is the imitation of the operation of a real-world process or system over time [9] and the main used techniques in the PSS context are: (a) Discrete Event Simulation, (b) Systems Dynamics, and (c) Agent-Based Simulation [10]. The most convenient simulation technique should be adopted depending on the specific analyzed PSS. A clear definition of these three simulation techniques as well as their advantages and disadvantages in the PSS context can be found in [10].

Once the PSS operation is simulated, exhibited *emergent attributes* must be measured. The measurement of the PSS cost is proposed to be performed by means of the *System Cost Uncertainty Analysis (SCUA)* technique, in which cost impacts of uncertainties associated with a system's configuration definition are quantified [5] [11]. SCUA uses an *Operational Cost Breakdown Structure (OCBS)* in order to represent the mathematical relationship (i.e. causal relationship establishment) between the PSS configuration and cost impacts. The use of OCBS represents a bottom-up parametric cost-determination approach in which historical data and statistical techniques are used in order to predict a future cost. The measurement of *performance* and *functionality* strictly depends on the specific analyzed PSS. In order to analyze any type of PSS from the proposed approach, a theoretical background for such *emergent attributes* have been developed and a case study has been carried out for the visualization of such proposal.

2.2. PSS Functionality

It is widely accepted that PSS brought a shift in the paradigm from selling products or services into an integrated value offer, where the customer looks for functionality instead of ownership [12]. Along PSS literature most of the authors employ the *functionality* concept as well as related concepts (cf. function) [13]. Nevertheless, little research work has been found in order to: (a) define the 'functionality' concept and (b) to represent such concept in a quantitative manner (i.e. how to measure it). In order to provide a definition for the *functionality* concept, it is highly important to realize that the introduction of a PSS as a business model entails a change of perspective from traditional business models focus on provider´s outcomes (i.e. PSS provider) into the PSS business model focus on customer´s outcomes. This does not imply that provider outcomes are no longer considered, but that the PSS must be seen as a system embedded in a supra-system owned by the customer, in which such customer outcomes are influenced by the PSS. With this in mind and based on the 'function' systematic treatment developed in [13], *function* and *functionality* concepts are constructed:

- *Function* is the intended purpose of the PSS configuration design. *Note that a PSS can have multiple functions.
- *Functionality* is the measurement of the PSS impact on customer outcomes.

It is easy to see the relationship between both concepts since *functionality* describes the PSS configuration ability to comply with the intended purpose for which the system was designed. Therefore, the *function* can be seen as the description of what the customer expects from the PSS and the *functionality* is the measurement of such impact.

2.3. PSS Performance

Performance describes the accomplishment of the PSS configuration measured against preset known standards, defining how well the PSS is generating its outcomes, delivering value and achieving objectives [14]. All relevant data in order to measure performance is obtained from information within PSS system boundaries. On the other hand, *functionality* relevant data is obtained when considering the impact of the PSS on the customer´s supra-system (i.e. outside PSS system boundaries). When analyzing *functionality*, both the PSS and the customer´s supra-system are looked as complex systems. Interconnections between both systems are established by means of its intended purposes (cf. teleological interconnection) in which a chain of functions links the systems in a certain configuration [5] (see Table 1).

Table 1. PSS Performance and Functionality Features

Features	**Performance**	**Functionality**
Focus	Provider's Outcomes	Customer's Outcomes
Analogous concepts	Capacity Efficiency	Capability Effectiveness
Measurement scope regarding system boundaries	Internal: Among components	External: With the supra-system
Measurement perspective regarding interconnections	Dependency: Input - Output relationship among components	Teleological: purpose relationship with the supra-system

To clearly understand the concepts of function, functionality and performance let us bring the example of Rolls-Royce contract with the US Navy in 2003 for the provision of maintenance, trouble-shooting, parts supply and logistical support for the Tubomeca F405 Adour engines that powered a 200 naval jets fleet [15]. The purpose of such contract (i.e. function) was to increase overall fleet flying time, where Rolls-Royce would receive a fixed price for each hour the engines were in air. The metric that measured how well Rolls-Royce system was deployed (i.e. performance) was ready-for-issue (RFI) engine availability, which is completely focused on the provider. Finally, considering the customer side, the impact of such contract on US Navy (i.e. functionality) was measured as the amount of flying hours per jet.

3. Case Study: Bergamo's Bike-Sharing System

In a bike-sharing system, citizens can rent a bike from a parking station, use it for the time needed, and return it to any other station around the city. Such PSS presents different positive impacts on involved stakeholders. From the *citizens' point of view,* the bike-sharing PSS provides higher flexibility, lower risks (e.g. bike stealing), and a possible way to move and to keep fit; from the *municipality perspective,* it provides higher connectivity, lower traffic congestion and less polluting emissions; and from the *bike-sharing PSS provider perspective,* it represents a new revenue source.

The bike sharing characteristics and the environmental gain related to the system make it a perfect example of a Product Service System (PSS). PSS indeed is *"a system of products, services, supporting networks, and infrastructure that is designed to be competitive, satisfy customers' needs, and have a lower environmental impact than traditional business models"* [16]. Among the many available policy and green solutions, bike-sharing systems are emerging as a cost-effective and sustainable way to expand the portfolio of transit options [17].

The city of Bergamo is located in Lombardy, Italy, about 40 km northeast of Milan. It has a bike sharing PSS, referred to as BiGi, since 2009. In the BiGi system, there are 22 stations for bicycle parking, covering a total area of 4.27 km^2 and providing 11.8 bikes per 1000 inhabitants. Currently, ATB (Azienda Trasporti Bergamo), the local public transport provider is managing the BiGi PSS.

The purpose of following case study is to visualize the proposed *PSS Cost-Engineering method* approach, techniques, and nature of results in relation with involved stakeholders using real historical data retrieved from [18] and BiGi website.

The main purpose of the method is to capture the emergent behavior of the PSS. As stated before, such emergence is observed when the PSS is operating, therefore, the scope of the method is limited to the PSS 'Use-stage' where determined costs are all relevant to the whole 'Operational Cost', and functionality measurement is restricted by functionality delivery at such stage. The method encompasses four main steps: (a) definition of PSS emergent attributes, (b) definition of PSS as a complex system, (c) stochastic process visualization, and (d) PSS cost determination. Proposed PSS cost engineering method is presented as follows.

3.1. PSS Emergent Attributes Definition

In this first step, the metrics and methodologies in order to measure the *functionality, performance and cost emergent attributes* are defined.

3.1.1. Functionality Definition

The definition of *functionality* requires the identification of *functions*. The most important *bike-sharing functions* have been retrieved from "The Bike-Share Planning Guide" [19], elaborated by the Institute for Transportation & Development Policy (ITDP). It is important to mention that in such planning guide, identified *functions* are not presented as 'functions', but as 'reasons for implementing bike-sharing systems', which is aligned with previously mentioned *function* definition. Identified functions are: (a) Reduce traffic congestion. Bike-sharing offers an alternative means of transport for short trips that might otherwise have been made by car. (b) Improve air quality. Bike sharing reduces the total amount of emissions displacing other modes of transportation. (c) Increase accessibility. Bike sharing gives local users greater access to places that are beyond their reach on foot. (d) Reduce "last mile" problem. Bike sharing fills the gap between the station or stop and the final destination. (e) Improve the health of the residents. Bike sharing offers an active transport mode, providing both physical and mental health benefits.

In order to reduce complexity of presented analysis, it is decided to select just one *function* (i.e. improve air quality by displaced modes of transportation) and one transportation mode (i.e. gasoline passenger cars). In that sense, the chosen key metric for such *functionality* definition is total avoided emitted tons of equivalent carbon dioxide per year (tCO2e/year). The ASIF framework as an on-road transportation emissions' calculation methodology was used for the measurement of Bergamo's Bike-sharing PSS Green House Gas Emissions Impact (i.e. reduction of emissions due to on-road transportation). Such methodology is found in "The Greenhouse Gas Protocol (GHG Protocol)" [20].

3.1.2. Performance Definition

The *performance emergent attribute* of the bike-sharing PSS is measured by means of Ready for Issue (RFI) PSS Availability. Such metric can be understood as the probability for users to find a bike in place ready for its use. In this manner, a better performance entails that the system is able to comply with more users, therefore as performance increases the total amount of trips increases. The measurement of performance emergent attribute can be done directly by means of *Discrete Event Simulation (DES),* which is appropriate for the analysis of systems whose change depends on the existence of defined events. In that sense, the state of the system is considered to be discrete, taking different values at particular time points, remaining in that state for some time between events. Some of the most important events in the bike-sharing PSS are arrival of customer to the bike station, retrieval of a bike, start of a trip, end of a trip, repair of a bike, among others.

Arena Simulation Software (Rockwell Automation) was used in order to construct the DES Model based on the Advanced Transfer Panel (ATP). Such panel enables the use of different modules needed for modelling the movement of entities from one location to another (e.g. stations, transporters). The simulation encompassed 1,000 replications, each representing a full operational year (i.e. 8,760 hours).

3.1.3. Cost Definition

It is defined that the *PSS cost emergent attribute* is measured by means of the *Average Cost per Trip,* since it is the most used operational cost metric in the bike-sharing context [19]. In order to carry out such measurement, the technique *System Cost Uncertainty Analysis (SCUA)* is used. Such technique enables the incorporation of random variation into the measurement of cost by the stochastic nature of the PSS operation. SCUA defines an *Operational Cost Breakdown Structure (OCBS)* that encompasses four main bike-sharing PSS operational elements: (a) cost drivers, (b) cost objects, (c) cost estimation relationships (CERs), and (d) CERs parameters. A brief explanation of such compounding elements is provided:

- *Cost Driver* is a factor that causes changes in the cost of an activity (e.g., maintenance cost drivers: staff, replacement parts, consumables, etc.).
- *Cost Object* is the measurable element of a cost driver (e.g. Maintenance staff = amount of people).
- *Cost Estimation Relationship (CER)* is a mathematical equation in which the cost driver is expressed as a dependent variable of one or more cost objects (e.g. maintenance staff = amount of people * average salary).
- *CER Parameters* are the elements that are expressed as constants in the CER (e.g. in maintenance staff = amount of people * average salary, such average salary is the constant).

The random variation in the cost measurement can be observed in the classification of cost drivers. Three types of cost drivers are proposed for such matter: (a) variable, (b) fixed-variable, and (c) fixed. *Variable cost drivers* are the ones that incorporate random variation into the cost measurement. The classification of a cost driver into one of these three types depends on the power of the PSS design stage to manipulate the impact that the cost driver exerts on the *total operational cost* and on the PSS operation.

- *Variable:* The impact that the cost driver exerts depends on the PSS operation and can be managed in the PSS design stage (e.g. the cost of redistribution fuel can be reduced if the initial number of bikes in each station is properly distributed - depends on the number of rebalanced bikes).
- *Variable - Fixed:* The impact that the cost driver exerts does not depend on the PSS operation; but can be managed in the PSS design stage (e.g., the cost of rebalancing staff depends on the number of people hired for such activity - does not depend on the number of rebalanced bikes).

- *Fixed:* The impact that the cost driver exerts does not depend on the PSS operation and cannot can be managed in the PSS design stage (e.g. the cost of software licensing is the same for any PSS configuration).

It is important to mention that *fixed cost drivers* are not included in the OCBS (for seeing Fig. 1. Bergamo's Bike-Sharing PSS - OCBS, click on https://goo.gl/rTiULw), since they do not depend on PSS configuration. Its value is added to the total final computed operational cost.

3.2. Complex System Definition

Once the *PSS emergent attributes metrics* and *methodologies* are defined, the PSS must be modelled from the *system thinking perspective.* In order to create such PSS model, the next statement must be clear: The DES model serves as the core aspect of the PSS as a complex system; it imitates the operation of such PSS. Both methodologies for the measurement of *cost* and *functionality* must be incorporated into the model to visualize the *emergence* of such attributes. In order to construct such PSS model, all *parameters* and *variables* from the DES, OCBS and the functionality measurement methodology must be considered. Such parameters and variables are quantitative representations of attributes of an analyzed entity. In a modelling sense, the difference strictly depends on what wants to be measured (i.e. what wants to be known), the nature of its measurement, and the design power to manipulate such values. In that manner, next definitions are provided:

- *Parameters* are known values that present a deterministic nature, and values can be manipulated in the design stage.
- *Independent Variables* are known values that present a deterministic or stochastic nature, and values cannot be manipulated in the design stage.
- *Dependent Variables* are unknown values that present a stochastic nature, and values cannot be manipulated in the design stage.

Such definition is called: *Universe of Parameters and Variables,* and describes the main interconnections among all defined parameters and variables, as well as their input-output (i.e. process-based thinking) dimension within the applied measurement methods. As it can be seen, the distinction between parameters and independent variables enables the visualization of the aspects that can be redesigned in the PSS configuration in order to improve it. The PSS configuration is defined as the set of established parameters that describe the infrastructure attributes of a PSS, and its value can be changed in the PSS design stage.

In the case study, such *universe* (for seeing Fig. 2. Bergamo's Bike-Sharing PSS – Universe of Parameters and Variables, click on https://goo.gl/yyor9U) encompassed 270 parameters, 630 independent variables and 21 dependent variables; modelled from the systems thinking approach in order to establish causal relationships.

3.3. Stochastic Process Visualization

Until this point, previous steps were developed in order to structure data and represent the proposed nature of the PSS. In this step the DES model is run and its output data (i.e. measurements of DES dependent variables) is stored in an excel file that Arena generates. Then, such DES output data is cleaned, inputted into the OCBS and ASIF methodology and processed by means of a R script, which is a language and environment for statistical computing and graphics. The result is a 1,000 observations (replications) data frame with three variables: performance, functionality and cost. The results are presented as follow in Fig. 1.

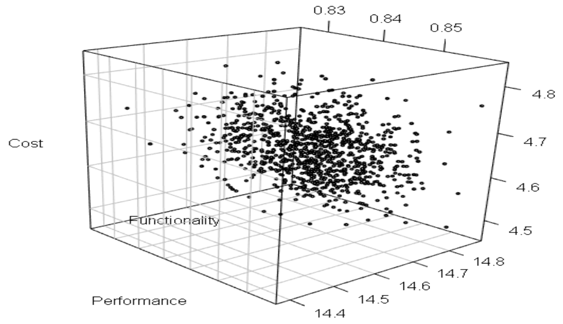

Fig. 1. Stochastic Process Results

The graphic in Fig. 1 represents the *stochastic process* of the bike-sharing PSS. Each data point corresponds to a replication (i.e. a complete year of operation) and contains the values of performance, functionality and cost. The main implication of having these three attributes simultaneously stored in one data point is that it enables to understand and measure how cost probabilities and potential outcomes are conditioned by analyzing a required level of PSS functionality and performance (an example is shown in next section). The method supports the processing of multiple *performance* indicators and multiple *functionalities* at the same time.

3.4. PSS Cost Determination

Another scrip in R was written in order to use obtained stochastic process data for the PSS cost-determination. Such determination is based on a *frequentist probability approach*, in which the determination of relevant probabilities is given by a *data points* counting process. Such interpretation of probability defines an event's probability as the limit of its relative frequency in a large number of trials.

In order to visualize how cost probabilities and potential outcomes are conditioned by analyzing a required PSS functionality and performance level, two scenarios: fulfillment and nonfulfillment, were constructed with following PSS performance and functionality requirements stated by relevant PSS stakeholders. *Requirements: customers expect that the bike-sharing PSS will provide at least 0.845 Ready for Issue (RFI) Bikes Availability, and the Municipality of Bergamo requires that the PSS avoid at least 14.7 tCO2e/ year. Fig. 2 shows the PSS cost-determination results, where *cost* is presented as a random variable, in which all-possible unrealized potential outcomes are depicted with their respective occurrence probability. Moreover, it is showed how in both proposed scenarios the cost is conditioned by defined performance and functionality stakeholders’ requirements; vertical lines represent *cost expected values.*

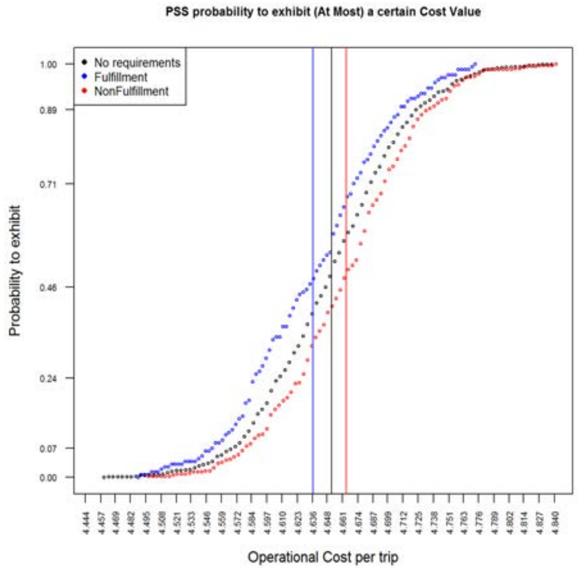

Fig. 2. PSS Cost Determination

As it can be seen, the nature of presented PSS Cost Determination results has important managerial implications, since the behavior of the cost, performance and functionality can be directly linked with relevant stakeholders’ requirements. In that sense, by the nature of the method´s output data, some foreseen PSS managerial applications are: (a) Redesign of PSS configuration, (b) Development of PSS pricing mechanisms, (c) Development of risk assessment analysis for stakeholders’ requirements fulfillment, and (d) Definition of PSS service level agreement.

4. Conclusions and Further Work

This research work proposes a *cost engineering method* for the PSS operational cost determination based on a *systems thinking approach* in which a PSS is seen as a *complex system* and its operational cost as an *emergent attribute.* From this approach, it is proposed to carry out a *stochastic process* that describes the *PSS behavior* by the evolution of *functionality, performance and cost variables.*

An empirical case study was developed in order to visualize the proposed *PSS cost engineering method’s* approach, techniques and results nature in relation with the involved stakeholders. The data output of the method represents all possible PSS cost unrealized potential outcomes with their associated occurrence probability, conditioned by a defined performance or/and functionality level. Given the nature of such resulting data, in which each data point represents the value for performance-functionality-cost simultaneously and since such values can be directly linked with relevant stakeholders’ requirements, proposed method´s output data entails important managerial implications.

Further work must be carried out in order to determine how to process method’s resulting data for the development of stated foreseen applications. Moreover, additional research must be done in order to broad current scope of the method (i.e. use-stage) into a lifecycle approach, where costs from the design/implementation/disposal stages are incorporated and proposed PSS emissions measurement technique is used for the construction of a LCA inventory.

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