Journal of Cleaner Production 228 (2019) 485–508

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

A rough-fuzzy DEMATEL-ANP method for evaluating sustainable value requirement of product service system

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A R T I C L E I N F O

Article history:
Received 4 November 2018
Received in revised form
8 April 2019
Accepted 13 April 2019
Available online 24 April 2019

Keywords:
Product service system
Sustainable value
Requirement elicitation
Requirement evaluation
Rough-fuzzy DEMATEL
Rough-fuzzy ANP

A B S T R A C T

Manufacturers are today striving to offer value-added Product Service System (PSS) with the purpose of achieving higher competiveness and more environmental benefits. Requirement elicitation and evaluation with sustainability concerns play a key role in a successful development of sustainable PSS. However, the previous literature rarely address the PSS requirement from the view of sustainability, while mainly focusing on the customer satisfaction. To accurately identify the requirement with respect to sustainable value from a long term perspective, it is necessary to develop effective methods for requirement elicitation for sustainable PSS. In addition, the prioritization of sustainable value requirement provides critical guidance for the later PSS design. The prioritization involves much judgement ambiguousness and diversity which may lead to inaccurate requirement analysis result. However, there are few researches on combinatory manipulation of the vagueness and diversity. Therefore, to solve these problems, an innovative methodology incorporating requirement elicitation and evaluation is developed for sustainable PSS. This study introduces the concept of value uncaptured into the identification of product value state, and offers the Product Value State Model (PVSM) method to elicit value requirements which help PSS deliver more sustainability. Moreover, a hybrid model for evaluating the sustainable value requirement is proposed by combining the fuzzy set, rough set, Decision Making Trial and Evaluation Laboratory (DEMATEL) and Analytical Network Process (ANP) methods. An application in an excavator PSS and the comparisons with some different methods demonstrate the feasibility and potential of the methodology. Theoretically, the proposed evaluation model provides more accurate and realistic analysis results of PSS requirements compared to traditional methods, since it supports to simultaneously manipulate judgement vagueness, group decision diversity, and complex interrelationship. In practical PSS design, the method helps PSS designers successfully recognize the most key value requirements with both respect of sustainability and customer satisfaction.

1. Introduction

Manufacturers in today's highly competitive market are endeavoring to achieve higher customer satisfaction and sustainability with more environment concerns, by providing individualized solutions with integrated bundle of product and value-added services (Parida et al., 2014). This offering integrated product and service is known as product service system (PSS) (Mont, 2002). PSS is a mix of tangible products and intangible services designed and combined so that they are jointly capable of fulfilling final customer needs in an economical and sustainable manner (Tukker and Tischner, 2006). Different with the conventional standardized product or service offerings, PSS are supposed to be integrated, lifecycle-oriented, sustainable and customized service solutions to flexibly satisfy customer's requirements and deliver environmental and social benefits (Song et al., 2015). Building on a true life-cycle costs perspective, PSS create incentives for optimizing energy and consumables, as well as prolonging a product's life (Tukker, 2004). Thus, the potential benefits of PSS that delivers offering integrated product and service solutions has economic, social, and environmental effects as companies improve resource utilization and competitiveness (Beuren et al., 2013; Boehm and Thomas, 2013).

A successful sustainable PSS needs to be carefully designed to embed sustainability concerns into each stage of product lifecycle (Khan et al., 2018). Requirement identification (elicitation) is

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https://doi.org/10.1016/j.jclepro.2019.04.145
0959-6526/© 2019 Published by Elsevier Ltd.

Notation list

Abbreviation

AHP	Analytic Hierarchy Process
ANP	Analytical Network Process
DEMATEL	Decision-Making Trial and Evaluation Laboratory
DM(s)	Decision-maker(s)
LFPP	Logarithmic fuzzy preference programming
MADM	Multi-attributes decision-making
MCDM	Multi-criteria decision-making
PSS	Product Service System
PVSM	Product Value State Model
VA	Value absence
VD	Value destroyed
VM	Value missed
VR(s)	Value requirement(s)
VS	Value surplus
VUP	Value uncaptured perspective

Symbols: Lowercase letters

$\tilde{a}$	Triangular fuzzy number
$\widehat{a}_{ij}$	Elements of group fuzzy pair-wise judgement matrix
$\widehat{a}_{ij}^{L}$	Lower limit of rough average number of triangular fuzzy judgement
$\widehat{a}_{ij}^{U}$	Upper limit of rough average number of triangular fuzzy judgement
d_{ij}^{lL}	Lower limit of low boundary of normalized rough-fuzzy element
d_{ij}^{lU}	Upper limit of low boundary of normalized rough-fuzzy element
d_{ij}^{mL}	Lower limit of medium boundary of normalized rough-fuzzy element
d_{ij}^{mU}	Upper limit of medium boundary of normalized rough-fuzzy element
d_{ij}^{uL}	Lower limit of up boundary of normalized rough-fuzzy element
d_{ij}^{uU}	Upper limit of up boundary of normalized rough-fuzzy element
l	Low boundary of triangular number
$\widehat{l}_{ij}$	Set of group low boundary of triangular fuzzy elements
l_{ij}^{L}	Lower limit of group low boundary of triangular fuzzy elements
l_{ij}^{U}	Upper limit of group low boundary of triangular fuzzy elements
m	Medium boundary of triangular number
$\widehat{m}_{ij}$	Set of group medium boundary of triangular fuzzy elements
m_{ij}^{L}	Lower limit of group medium boundary of triangular fuzzy elements
m_{ij}^{U}	Upper limit of group medium boundary of triangular fuzzy elements
r_{ij}^{k}	The kth class of human judgement
r_{ij}^{kL}	Lower limit of rough number of the kth judgement
r_{ij}^{kU}	Upper limit of rough number of the kth judgement
r_{ij}^{L}	Lower limit of average rough number of group judgements
r_{ij}^{U}	Upper limit of average rough number of group judgements
t_{ij}	Crisp value of normalized dependence matrix
t_{ij}^{L}	Lower limit of element of rough dependence matrix
t_{ij}^{lL}	Lower limit of low boundary of total rough-fuzzy element
t_{ij}^{lU}	Upper limit of low boundary of total rough-fuzzy element
t_{ij}^{mL}	Lower limit of medium boundary of total rough-fuzzy element
t_{ij}^{mU}	Upper limit of medium boundary of total rough-fuzzy element
t_{ij}^{U}	Upper limit of element of rough dependence matrix
t_{ij}^{uL}	Lower limit of up boundary of total rough-fuzzy element
t_{ij}^{uU}	Upper limit of up boundary of total rough-fuzzy element
u	Up boundary of triangular number
$\widehat{u}_{ij}$	Set of group up boundary of triangular fuzzy elements
u_{ij}^{L}	Lower limit of group up boundary of triangular fuzzy elements
u_{ij}^{U}	Upper limit of group up boundary of triangular fuzzy elements
x_i	Element of lower approximation
x_i^{L*}	Optimal solution of logarithmic fuzzy preference programming for lower limit comparison matrix
x_i^{U*}	Optimal solution of logarithmic fuzzy preference programming for upper limit comparison matrix
y_i	Element of upper approximation
$\tilde{z}_{ij}^{s}$	Triangular fuzzy number of element in the initial direction relation matrix
$\widehat{z}_{ij}$	Set of group triangular fuzzy elements
$\widehat{z}_{ij}^{L}$	Lower limit of average rough number of group triangular fuzzy elements
$\widehat{z}_{ij}^{U}$	Upper limit of average rough number of group triangular fuzzy elements

Capital letters

$\tilde{A}$	Group fuzzy pair-wise judgement matrix
$\tilde{A}_k$	Fuzzy pair-wise judgement matrix made by the kth DM
$\underline{Apr}$	Lower approximation of judgement
$\overline{Apr}$	Upper approximation of judgement
J	Set of human judgements
N_i^{L}	Number of objects included in the lower approximation
N_i^{U}	Number of objects included in the upper approximation
$\underline{Lim}$	Lower limit of human judgement
$\overline{Lim}$	Upper limit of human judgement
$RN(\tilde{A})$	Rough-fuzzy pair-wise judgement matrix
$RN(\tilde{D})$	Rough-fuzzy normalized direct-relation matrix

$RN(\widehat{d}_{ij})$	Element of rough-fuzzy normalized direct-relation matrix
$RN(\widehat{l}_{ij})$	Average rough number of group low boundary
$RN(l^s_{ij})$	Rough number of low boundary of triangular fuzzy element
$RN(m^s_{ij})$	Rough number of medium boundary of triangular fuzzy element
$RN(\widehat{m}_{ij})$	Average rough number of group medium boundary
$RN(\widehat{r}_{ij})$	Average rough number of group judgements
$RN(r^k_{ij})$	Rough number of human judgement
$RN(T)$	Rough dependence matrix
$RN(\tilde{T})$	Rough-fuzzy total direction matrix
$RN(u^s_{ij})$	Rough number of upper boundary of triangular fuzzy element
$RN(\widehat{u}_{ij})$	Average rough number of group up boundary
$RN(W)$	Rough priority vector
$RN(\tilde{Z})$	Rough-fuzzy initial direct-relation matrix
$RN(\widehat{z}_{ij})$	Element of rough-fuzzy initial direct-relation matrix
T	Crisp dependence matrix
T_N	Normalized dependence matrix
U	Universe including all the human judgements
VRi	the ith value requirement group
$VRij$	the jth value requirement of the ith requirement group
W	Limit supermatrix
W_I	Initial supermatrix
W^L	Priority vector of lower limit comparison matrix
W^N	Normalized priority vector
W_{NW}	Normalized weighted supermatrix
W^U	Priority vector of upper limit comparison matrix
W_W	Weighted supermatrix
Y	Arbitrary object of judgements universe
$\tilde{Z}$	group fuzzy initial direct-relation matrix
$\tilde{Z}_s$	Fuzzy initial direct-relation matrix made by the sth DM
Greek letters	
λ	Optimistic indicator used in rough-fuzzy DEMATEL
β	Optimistic indicator used in rough-fuzzy ANP

widely acknowledged as the beginning of a PSS design (Berkovich et al., 2014). Different with the conventional requirement identification whose focus is mainly on the satisfaction of wishes and expectations of the customer and stakeholders (Nuseibeh and Easterbrook, 2000), the requirement identification of sustainable PSS considers the value delivered to stakeholders from a long term perspective as well as the environmental and social aspects (Hart and Milstein, 2003; Yang et al., 2013). In this respect, the requirements of sustainable PSS is elicited from the sustainable value that is continuously proposed, created and delivered to customers during the use life of product. However, most of the previous elicitation methods is usually developed for traditional PSS, missing the sustainability concerns. After the PSS requirement is recognized, the requirement should be prioritized for the later design decision. Requirement evaluation is acknowledged as an important activity in PSS development. Designer team should establish the relative priorities of requirements under the constraint resource. The requirement evaluation always takes different suggestions from multiple stakeholders such as customers, designers, suppliers, etc. Thus, evaluation of PSS requirement involves much ambiguous human perceptions and subjective judgments, which will lead to the inaccurate requirement specification and priority. Most of the previous research have omitted the manipulation of both linguistic judgement vagueness and group decision diversity. Moreover, there is a lack of systematic methods for eliciting and evaluating the sustainable PSS requirements under vague and diversified decision environment in past research.

Therefore, in this paper, a systematic methodology for identifying and evaluating sustainable value requirement of PSS is developed. Aiming to elicit and configure the sustainable value requirement of PSS, a new Product Value States Model (PVSM) is proposed. The PVSM is inspired by the new value uncaptured perspective (VUP)-based framework proposed by Yang et al. (2017). The VUP provides a holistic understanding of value systems by defining value uncaptured as four forms including value surplus (VS), value absence (VA), value destroyed (VD), and value missed (VM). The VUP-based framework helps the firms identifying the value uncaptured of different forms hidden in their current business models. And it provides support to turn those obtained value uncaptured into new sustainable value proposition. However, the VUP is mainly applicable in business model innovation at the enterprise level, while not specifically adaptive to design the sustainable PSS. Contrary to the VUP-based framework, the PVSM redefines the value states in the product use life as five forms: value captured, value failed, value missed, value deteriorated, and value surplus. The model helps unlocking the new value opportunities which are inherently hidden in each value state along the current product use life. The new value opportunities can be turned into new product service requirements. In this respect, the PVSM is a novel tool to facilitate sustainable value innovation, and identify requirements for achieving more sustainability of PSS. Those identified requirements are then organized into a hierarchical structure for their related importance evaluation.

Additionally, a hybrid evaluation model for sustainable value requirement is proposed by integrating the rough set, fuzzy set, DEMATEL, and ANP method. The ANP method has advantages of prioritizing groups of elements with consideration of both dependences and independences of elements (Büyüközkan and Güleryüz, 2016; Meade and Sarkis, 1999). Since the value requirement of PSS is organized in an interrelated hierarchical structure based on PVSM, it is rational to apply the ANP method. On the other hand, ANP has certain disadvantages. Since the ANP requires pairwise comparison of elements and all the pair-wise judgement matrices should be examined the consistency, it brings about the low efficiency and distortion to the decision results as well as the increasing complexity with the number of elements. By integrating the ANP with the DEMATEL method, the complexity of the problem can be reduced and the global influence strength of an element on others also can be identified. The DEMATEL method does not require comparison of all pairs of elements, significantly reducing the complexity of decision operation (Tadić et al., 2014). Therefore, in the proposed evaluation model, the DEMATEL and ANP method are adopted for determining the dependences between value requirements belonging to the same group and among the different groups, respectively. However, the group decision-makers' (DMs') judgements on value requirements are often vague and diversified, which may lead to inaccurate requirement evaluation. Fuzzy set theory (Zadeh, 1965) is applied in this method due to its effectiveness of manipulating the vagueness in thinking and expressing preferences of DMs (Ngan et al., 2018). The rough set method is used for aggregating the group fuzzy judgements since it is feasible to manipulate the diversity and subjectivity of multiple DMs (Zhai et al., 2008). The combination of the fuzzy set and rough set makes both use of the strength of fuzzy method in coping with the vagueness of single DM and the merits of rough method in handling the diversity of multiple DMs. Different with the previously used DEMATEL, ANP or combined DEMATEL-ANP methods (Tzeng and Huang, 2011), this research integrates group DEMATEL-ANP method and rough-fuzzy logic together to obtain the dependences between requirements in a diversified and fuzzy decision environment. In this respect, the proposed rough-fuzzy DEMATEL-ANP is innovative in this field. Compared with the conventional evaluation methods, the proposed model is more accurate to describe the realistic status of value requirement and more feasible to simplify the complex evaluation problem and reduce the calculation work. To the best of authors' knowledge, although the DEMATEL-ANP, fuzzy DEMATEL-ANP and rough DEMATEL-ANP have been applied in Multi-criteria Decision-making (MCDM) fields, alone or in combination with other methods, there are no examples in the literature of combining the rough set, fuzzy set and DEMATEL-ANP methods in the vague and heterogeneous decision environment.

Thus the main contributions and novelty of this study are as follows:

1. This paper contributes to PSS and sustainability theory by introducing the concept of value uncaptured into the identification of sustainable value requirement of PSS, and offers the PVSM-based method to elicit value requirements which have high potential to help PSS deliver more sustainability (e.g. improve product efficiency, reduce product downtime, increase utilization rate, prolong use life, etc.).
2. This paper contributes to decision theory by proposing a novel rough-fuzzy DEMATEL-ANP methodology that provides useful reference for researchers to simultaneously manipulate judgement vagueness, group decision diversity, complex interrelationship, and heavy calculation workload in evaluation problem or other MCDM fields. Notably, the integration of fuzzy set and rough set theory gives a feasible approach to obtaining more realistic perception of the ambiguous and subjective human evaluation.
3. This paper contributes to PSS design methodology by using the present evaluation model to obtain more accurate and objective prioritization of sustainable value requirements of PSS in a vague and diversified environment. The model helps PSS designers successfully recognize the most key value requirements with both respect of sustainability and customer satisfaction.

The structure of the rest of this paper is organized as follows. In Section 2, some of the past literature relating to PSS, PSS requirement, and methods for identifying and evaluating requirement of sustainable PSS is reviewed. In Section 3, the both proposed PVSM-based elicitation method and rough-fuzzy DEMATEL-ANP evaluation model for sustainable value requirement are described. In Section 4, an application of the proposed method in an excavator PSS and the comparisons with some different methods are illustrated. In Section 5, the theoretical and practical implications of the proposed methodology are explained. Finally, according to the findings of this research, conclusions and suggestions are presented in Section 6.

2. Literature review

2.1. PSS and PSS requirement

PSS has been studied by researchers from a wide range of fields and considered as a pioneering innovation of business models for sustainability (Reim et al., 2015). Tukker (2004) categorized the PSS into three types: product-oriented PSS (e.g., maintenance and repair) which is adding services to current products, use-oriented PSS (e.g., product renting, sharing, and pooling) which is intensifying the use of products, and result-oriented services focusing on customer requirements fulfillment. All the PSS types have the potential of increasing the commercial and environmental sustainability (Tukker and Tischner, 2006). For example, sharing the idle product to other users aiming at maximizing profits (Piscicelli et al., 2018) enable satisfying needs without physical ownership of product and prolonging product life (Merli et al., 2018), with presenting high sustainable potential for business innovation (Romero et al., 2017); the provision of the preventative maintenance for the product contributes to reducing the probability of failure or preventing degradation of the functioning of a product, thus improves the sustainability due to the prolonged use life and enhanced operational performance (Khan et al., 2018; Wu and Zuo, 2010); the use- and result-oriented PSS could deliver a higher potential to be dematerialized due to the retaining of ownership for manufacturer (Beuren et al., 2013). From the previous research, the sustainability of PSS has been widely acknowledged. However, it does not imply that PSS would inherently bring sustainable effects (Yang et al., 2014). The development, implementation and operation of sustainable PSS are still challenging (Vezzoli et al., 2012).

As one of the most important, difficult challenges, PSS development deserves more research and exploration. In the domain of engineering design, requirement is believed to be success factor of product development projects (Ulrich, 2003). Requirement is defined as a request that a product fulfills certain properties or functions, and it consists of a describing attribute and a defining value (quantification) (Jung, 2006). A requirement is a defined behavior, characteristic or property, to be assumed for an object, a person or an activity which has to assure a certain result in a value creation process (Song, 2017). In the context of sustainable PSS, requirement involves the sustainable object, stakeholders, activities and sustainable values. The requirement has been recognized as a critical factor influencing delivered quality of solution (Song et al., 2013). In this respect, sustainable PSS requirement is one of the fundamental driving force for service- and sustainability-oriented manufacturing transformation (Song, 2017). Thus, the accurate requirement identification, rational analysis and effective mapping is critical to obtain a satisfactory design solution for sustainable PSS.

2.2. Requirement identification of sustainable PSS

Much research has explored the identification methods or tools of sustainable value and elicitation method of PSS requirement. A 'value mapping tool' was developed by Bocken et al. (2013) for unlocking sustainable value opportunities through analyzing value exchanges from the perspective of multiple stakeholders, while this tool neither consider the lifecycle nor be specifically designed for PSS. This tool proposes two important concepts of value destroyed (VD) and value missed (VM) to present the negative aspects of a current business model. Yang et al. (2013) integrated these two concepts with another newly introduced two concepts of value surplus (VS) and value absence (VA) into the establishment of a 'PSS life cycle sustainable value analysis tool'. This tool helps capturing new sustainable value opportunities through the entire life cycle of product and drive value movement to achieve a more sustainable value proposition. Progressively, Yang et al. (2014) extended the sustainable value analysis tool by embedding the environmental and social concerns with the object of identifying opportunities for sustainable value creation in the process of PSS development. Furtherly, Yang et al. (2017) developed a value uncaptured perspective-based framework incorporating the four value forms of VS, VA, VD and VM to help firms identify sustainable value in current business model. The framework includes two main steps, i.e. identifying the value uncaptured in current business model and then turning the obtained value uncaptured into new business opportunities. However, this framework is mainly used in an enterprise environment without considering the implementation in PSS development. Additionally, some other value analysis tools/methods have been explored in the previous research, such as the Stakeholder Value Network approach (Hein et al., 2017), Business Model Canvas (Heyes et al., 2018), etc. Although these value analysis methods are widely applied for recognizing value proposition for business model innovation, they are not specifically intended to be used in the context of sustainable PSS.

The sustainable value identified by utilizing some value analysis methods is regarded as the key sources of sustainable PSS requirement. Requirements identification and processing is the key to successful product/service design and delivery (Song and Sakao, 2017). The task of requirements elicitation is the identification of requirements' sources and the elicitation of requirements according to the identified stakeholder value and other sources. However, there are fewer studies on requirements identification of PSS in the past (Mannweiler and Aurich, 2011). Some requirements identification approaches and their features' analysis are summarized as follows. Berkovich et al. (2014) have developed a requirements data model for helping achieve requirement concretization but not requirement generation, i.e. this model presents the clear structure for the requirements directly without giving the identifying process. Song et al. (2013) have proposed a model of industrial customer activity cycle (I-CAC) to identify explicit requirements from each stage of customer activity, without revealing the implicit requirements. Long et al. (2013) identified the PSS requirement through collecting the customers' expression of functional needs and perception needs. Ota et al. (2013) integrated the scenario planning methodology with template-based approach to elicit requirements in the consideration of the external factors. Hussain et al. (2012) developed a framework using system-in-use data only for understanding the customer's deeper requirements without recognizing the stakeholder' involvement.

2.3. Requirement evaluation of sustainable PSS

Requirement evaluation contributes to assisting the designers in making trade-off decisions for further PSS concept planning and resources allocation. Its implementation should consider four essential factors: flexible evaluation structure, linguistic vagueness, judgement diversity, and requirement interaction (Song, 2017). De Felice and Petrillo (2010) utilized the AHP method to prioritize the customer needs and functional characteristics with flexible evaluation structure. Since the human judgement made from different DMs on requirements are always subjective and diversified. The conventional AHP is inadequate to deal with the judgement vagueness, diversity and the interaction between requirements. To manipulate the linguistic vagueness, Nepal et al. (2010) presented a fuzzy set theory-based AHP for obtaining the related weights of requirements in target planning. It is indicated the fuzzy method can effectively capture human perception. Song et al. (2013) proposed a feasible solution for manipulating judgement diversity by applying rough set into AHP method to aggregate the group assessments on industrial PSS requirements. However, these AHP-based methods do not consider the requirement interactions. Zhou et al. (2008) used a fuzzy ANP approach to manipulate the interdependence between requirements, as well as handle the vague linguistic expression on the importance of requirement. However, fuzzy set-based ANP has two shortcomings including the heavy calculation workload of a large amount of comparison matrices and the unsuitability for group evaluation process. Geng and Chu (2012) stated a fuzzy DEMATEL method to analyze the mutual influence relationships among PSS requirements, which reduce the evaluation complexity and calculation workload. Song and Cao (2017) proposed a rough DEMATEL to evaluate the interactions among PSS requirements under group decision environment. Song and Sakao (2018) extended the rough DEMATEL method to assess the individualized PSS. Liu et al. (2019) integrated the interval-valued hesitant fuzzy DEMATEL method to evaluate co-creative value propositions for smart PSS. Inherently, these DEMATEL-based methods are not appropriate for evaluating requirements in large number. The combinations of ANP and DEMATEL (Tzeng and Huang, 2011) which are applied in other fields such as green supplier selection (Chatterjee et al., 2018), group multi-criteria decision making (Pamučar et al., 2017), business partner evaluation (Büyüközkan et al., 2017), etc., have shown the integrated strength of ANP in coping with complex relationships and merits of DEMATEL in obtaining global influence of evaluation object.

The previous studies have widely explored the requirement identification and evaluation of general PSS, while the context of sustainable PSS has not been specifically concerned. The entire logic solution for identifying and prioritizing the sustainable value requirement is still omitted. Although several previous works attempt to provide some valuable insights into the identification of sustainable value of PSS, most of them remain largely conceptual and are difficult to apply in the practical design of sustainable PSS. Moreover, most of the previous approaches of requirements elicitation do not embed the sustainability concerns into the requirements elicitation. In addition, a majority of the previous requirement evaluation methods are not suitable in the vague and heterogeneous group decision environment. Therefore, to fulfill these research gaps, it is necessary to develop a systematic method for eliciting and evaluating requirement of sustainable PSS in group decision process.

3. Evaluation methodology for sustainable value requirement of PSS based on the PVSM and rough-fuzzy DEMATEL-ANP

3.1. Overview of the methodology

This paper proposes a novel hybrid methodology involving elicitation and evaluation methods for sustainable value requirement of PSS. This method is applicable for group DMs including the customers, designers and related managers. As shown in Fig. 1, the whole model is divided into two stages, namely, *Stage I* and *II*. *Stage I* is mainly focusing on elicitation of the sustainable value requirement of PSS with construction of Product Value States Model (PVSM) and value requirement structure. *Stage II* describes the mathematic evaluation methodology of sustainable value requirement which incorporates the rough-fuzzy DEMATEL and rough-fuzzy ANP method. The fuzzy set and rough set are combined to manipulate the vagueness of single DM and the diversity of multiple DMs. The rough-fuzzy ANP method is developed by gathering the rough-fuzzy method and ANP model together with the purpose of establishing the dependences among the value requirements belonging to different groups. In addition, integration of the ANP with the DEMATEL method could help to effectively reduce the evaluation complexity. The rough-fuzzy DEMATEL method is adopted for determining the dependences between value requirements belonging to the same group.

3.2. Elicitation of sustainable value requirement of PSS based on PVSM

Elicitation of sustainable value requirement of PSS is the beginning of sustainable PSS development project. This section firstly introduces a value uncaptured perspective into construction of Product Value State Model (PVSM) in order to recognize the

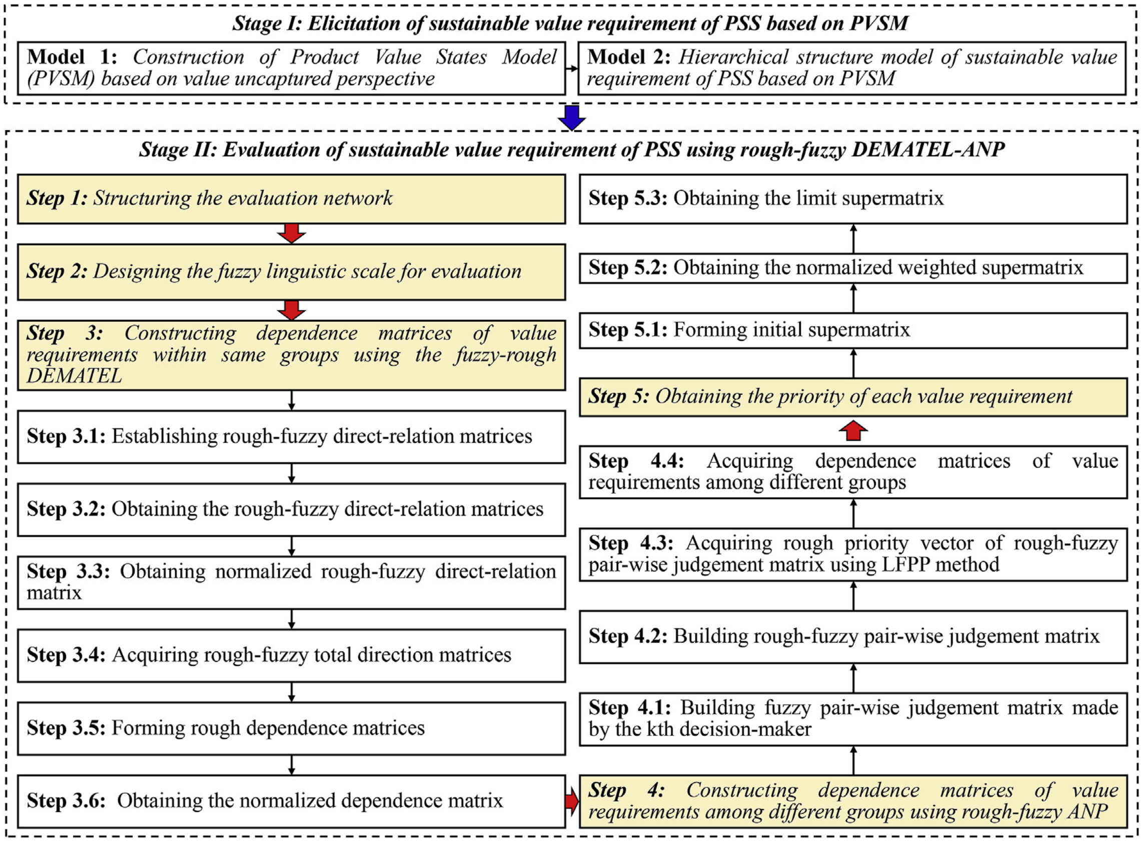


Fig. 1. Research methodology for systematical evaluation of sustainable value requirement of PSS.

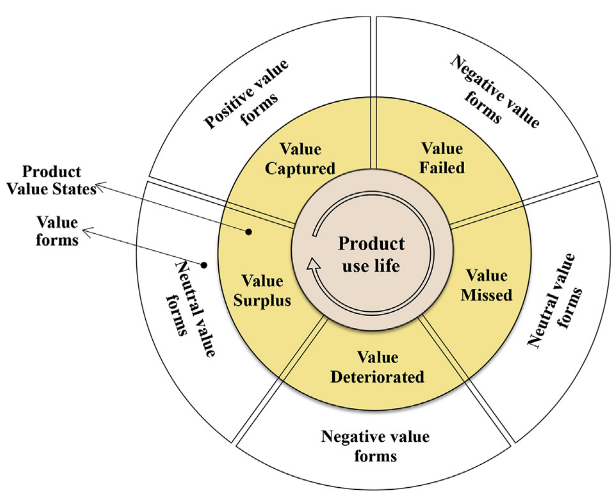


Fig. 2. Product value states model (PVSM).

sustainable value of PSS. Secondly, the process of eliciting requirements from sustainable value proposition is described. Thirdly, the identified sustainable value requirements are organized into hierarchical structure for further evaluation.

3.2.1. Construction of PVSM

The PVSM is proposed with the purpose of identifying the sustainable value of the PSS. The PVSM is inspired by the value uncaptured perspectives proposed by Yang et al. (2014). The proposed PVSM mainly focuses on identifying the value uncaptured in the use life of product, contrary to Yang's framework which is used in the enterprise level (Yang et al., 2017). The model provides supporting to recognize new value opportunities in current product use life. The new value opportunities can be turned into new product service requirements. As shown in Fig. 2, the product value state in the use life of product is classified as five forms, namely, value captured, value failed, value missed, value deteriorated and value surplus. The detailed descriptions of value states are introduced as follows:

- Value captured (*VC*) is value which is captured or used to satisfy the demanders' functional requirements. The value is captured in the interaction between demanders and product, i.e. only if the value of product is being utilized in achieving the desired functionality, it can be called value captured. A practical example could be that when customers are using an automobile to reach the destination, the value of the automobile is captured.
- Value failed (*VF*) is value which is temporarily unable to be used due to its unexpected failure. The value of product is failed when the product shut down urgently caused by some random failure. It is a negative form of product value for customers as it causes a low efficient product use or even harmful effects. For example, when an automobile cannot work due to some unexpected stoppage, the value of automobile is failed.
- Value missed (*VM*) is value which exists but not be used. It can be but not be captured to satisfy requirements. It is currently squandered or inadequately captured by the customers. When the product is idle or underutilized, its current value is missed where more value could be created. The value missed does not bring about negative outcomes but reduce the total value that can be captured for the product. It can be shared to other customers to create new value. Examples could be an underutilized production machine or an idle automobile with good performance.
- Value deteriorated (*VD*) is value which is in a lower value level. It does not have sufficient ability to satisfy the customers'

requirements. Probably, it may bring about negative outcomes with high potential to cause bad experience and disadvantages to the customers. It exists in the decreasing process of product performance. A specific example could be that, when the performance of an automobile is in degradation after its long time operation, it has an increasing probability of causing bad experiences to customers or even safety problems to society and environments.

- Value surplus (*VS*) is value which exists but is not required anymore. When a product cannot meet the necessary requirements from customers, it will be abandoned or disposed as waste. It offers high potential to be turned into value opportunities, such as recovery, reuse and reproduce etc. Examples include the scraped automobile, discarded parts of engineering equipment.

In this model, each product value state presents different value form. Value captured is a positive value form of a product, which brings about useful value to the customers. It still has a potential to create new value opportunities since the customer always tends to an optimal operation of product. The value opportunities refer to any activities that can capture, create and deliver new value to the stakeholders. The value with negative forms are what customers do not want, since they will harm or reduce the customers' value. The value opportunities exited in each value states may differ in different value forms. They can be described as the product extension services which are required to reduce the negative forms of value states and turn the value uncaptured into positive profits.

3.2.2. Sustainable value proposition and requirement elicitation

Based on the PVSM, new value opportunities can be found in each product value state. The new value opportunities are identified to create sustainable value proposition. The value proposition is the added benefit obtained by the customers from each value states. It can be regarded as a common value requirement goal for stakeholders related with PSS. The expression for value proposition can be a sentence clearly describing the added value provided by the new PSS in different product value states. The value proposition in value captured and value missed are taking as examples: when the product is in value captured, an optimal operation of product is always desired by the customer; and when the product is in value missed, sharing the product to other users to obtain extra incomes is the value proposition for the customer. Since the value proposition is conducted, the related value requirements could be elicited by gathering and collecting the information from the customers and the product operation in utilization of some methods. Those methods include, for instance, interviews, focus groups, brainstorming, use cases, checklists and questionnaires. Orienting to the value proposition 'optimization of product operation', value requirements such like operational optimization, energy consumption saving, utilization improvement and throughput improvement e.g. are elicited (see Fig. 3).

3.2.3. Construction of hierarchical structure for sustainable value requirement of PSS based on PVSM

As mentioned in the review and analysis in Section 2, it is necessary to develop a more effective approach to systematically evaluating the PSS value requirement. Owing to the diversified, imprecise and linguistic characteristic of value requirements, the first step should be grouping them into categories. It is obviously shown in Fig. 2 that each product value state is independent to each other. The value requirements elicited from the same value state are arranged into the same group. This grouping form help the PSS designers to prioritize the value requirements based on their influences on the sustainability of the system. With this grouping method, value requirements are organized as a tree-like structure with a rising number of items from up to down as shown in Fig. 4. Furthermore, this evaluation structure lays a further basis for selecting the service modules.

3.3. Evaluation methodology of sustainable value requirement of PSS

As the proposed model involves the application of the fuzzy set and rough set which are separately used to manipulate the judgement vagueness and diversity, some basic features of triangular fuzzy numbers, rough numbers, and some basic operations on them have been described as follows.

3.3.1. Triangular fuzzy numbers and basic operation on them

Fuzzy set theory is a mathematical theory first introduced by Zadeh (1965), which is designed to model the vagueness or imprecision of human cognitive processes (Tadić et al., 2014). It is indicted by fuzzy set theory that the elements have a degree of membership in a fuzzy set. A triangular fuzzy number denoted as $\tilde{a} = (l, m, u)$ where $l \le m \le u$, whose membership function is $f_{\tilde{a}}(x)$ as follows:

$$f_{\tilde{a}}(x) = \begin{cases} 0, & x < l \quad \text{or} \quad x > u \\ \dfrac{x-l}{m-l}, & l \le x \le m \\ \dfrac{u-x}{u-m}, & m \le x \le u \end{cases} \tag{1}$$

The basic operation of triangular fuzzy number are as following Eq. (2)~(5) (Sun, 2010).

Addition of the fuzzy number:

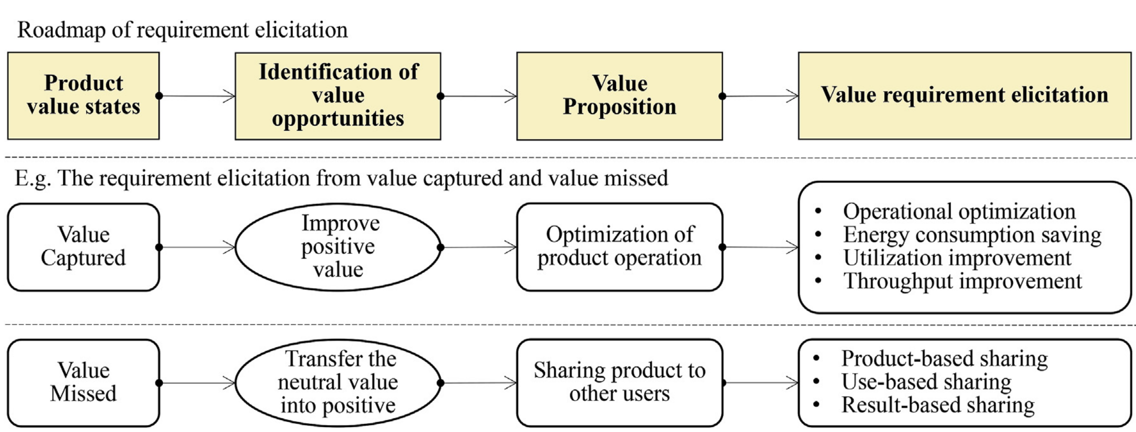


Fig. 3. Sustainable value requirement elicitation from PVSM.

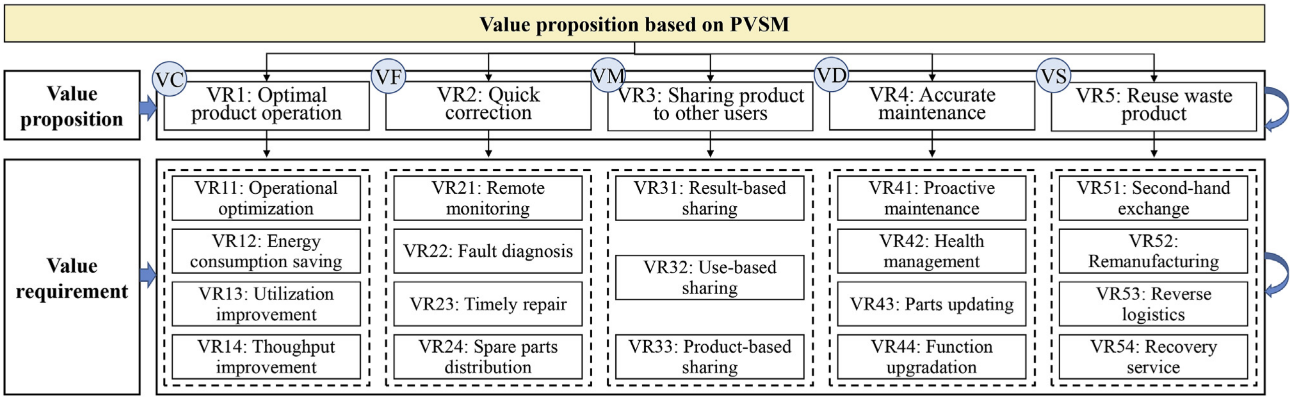


Fig. 4. Hierarchical structure of PSS sustainable value requirement.

$$\tilde{a}_1 + \tilde{a}_2 = (l_1, m_1, u_1) + (l_2, m_2, u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \quad (2)$$

Multiplication of the fuzzy number:

$$\tilde{a}_1 \times \tilde{a}_2 = (l_1, m_1, u_1) \times (l_2, m_2, u_2) = (l_1 l_2, m_1 m_2, u_1 u_2) \quad (3)$$

for $l_1, l_2 > 0, m_1, m_2 > 0, u_1, u_2 > 0$.

Subtraction of the fuzzy number :

$$\tilde{a}_1 - \tilde{a}_2 = (l_1, m_1, u_1) - (l_2, m_2, u_2) = (l_1 - l_2, m_1 - m_2, u_1 - u_2) \quad (4)$$

Division of the fuzzy number:

$$\tilde{a}_1 \div \tilde{a}_2 = (l_1, m_1, u_1) \div (l_2, m_2, u_2) = (l_1/u_2, m_1/m_2, u_1/l_2) \quad (5)$$

for $l_1, l_2 > 0, m_1, m_2 > 0, u_1, u_2 > 0$.

3.3.2. Rough numbers and basic operation on them

Assume that there is a set of m classes of human judgements, $J = \{r_{ij}^1, r_{ij}^2, \ldots, r_{ij}^k, \ldots, r_{ij}^m\}$ is ordered in the manner of $r_{ij}^1 < r_{ij}^2 < \ldots < r_{ij}^k < \ldots < r_{ij}^m$. U is the universe including all the objects and Y is an arbitrary object of U, and then the lower approximation of r_{ij}^k and the upper approximation of r_{ij}^k can be defined as:

Lower approximation:

$$\underline{Apr}\left(r_{ij}^k\right) = \cup\left\{Y \in U/R(Y) \le r_{ij}^k\right\} \quad (6)$$

Upper approximation:

$$\overline{Apr}\left(r_{ij}^k\right) = \cup\left\{Y \in U/R(Y) \ge r_{ij}^k\right\} \quad (7)$$

Then, the judgement, r_{ij}^k can be represented with a rough number defined by its lower limit $\underline{Lim}(r_{ij}^k)$ and upper limit $\overline{Lim}(r_{ij}^k)$ as follows:

$$\underline{Lim}\left(r_{ij}^k\right) = \left(\prod_{m=1}^{N_i^L} x_i\right)^{1/N_i^L} \quad (8)$$

$$\overline{Lim}\left(r_{ij}^k\right) = \left(\prod_{m=1}^{N_i^U} y_i\right)^{1/N_i^U} \quad (9)$$

where x_i and y_i are the elements of lower and upper approximation for r_{ij}^k, N_i^L and N_i^U are the number of objects included in the lower approximation and upper approximation of r_{ij}^k, respectively.

The rough number form $RN(r_{ij}^k)$ of r_{ij}^k can be obtained using Eq. (6)~(10):

$$RN\left(r_{ij}^k\right) = \left[\underline{Lim}\left(r_{ij}^k\right), \overline{Lim}\left(r_{ij}^k\right)\right] = \left[r_{ij}^{kL}, r_{ij}^{kU}\right] \quad (10)$$

where r_{ij}^{kL} and r_{ij}^{kU} are the lower limit and upper limit of rough number $RN(r_{ij}^k)$. The interval of boundary region r_{ij}^{kU}-r_{ij}^{kL} indicates the degree of vagueness. A rough number with a smaller interval of boundary region is interpreted as more precise one.

The average rough number $RN(\hat{r}_{ij})$ can be obtained by using rough computation principles (11)–(13):

$$RN(\hat{r}_{ij}) = \left[r_{ij}^L, r_{ij}^U\right] \quad (11)$$

$$r_{ij}^L = \left(\prod_{k=1}^{m} r_{ij}^{kL}\right)^{1/m} \quad (12)$$

$$r_{ij}^U = \left(\prod_{k=1}^{m} r_{ij}^{kU}\right)^{1/m} \quad (13)$$

where r_{ij}^L and r_{ij}^U are lower and upper limit of rough number $RN(\hat{r}_{ij})$ respectively, and m is the number of decision-makers.

3.3.3. Evaluation of sustainable value requirement of PSS using rough-fuzzy DEMATEL-ANP

In this section, a hybrid model combined rough-fuzzy DEMATEL and rough-fuzzy ANP is proposed for the purpose of the evaluation

Table 1
Linguistic terms and corresponding fuzzy values (Tadić et al., 2014).

Linguistic term	Abbreviations	Fuzzy scales
None	N	(0.1,0.1,1)
Very low	VL	(0.1,1,2)
Low	L	(1,2,3)
Fairly low	FL	(2,3,4)
More or less low	ML	(3,4,5)
Medium	M	(4,5,6)
More or less high	MH	(5,6,7)
Fairly high	FH	(6,7,8)
High	H	(7,8,9)
Very high	VH	(8,9,10)
Extremely high	EH	(9,10,10)

for sustainable value requirement of PSS. The computational steps of the hybrid model are explained as follows.

Step 1. structuring the evaluation network

As described above, the sustainable value requirements can be organized as a tree-like structure based on the PVSM. The evaluation problem is structured into a triple-layered network shown in Fig. 4. This network is used to evaluate the value requirement with considering the relations among the value requirements. *VRi* denotes the *i*th value requirement group, and *VRij* denotes the *j*th value requirement of the *i*th requirement group.

Step 2. selecting the fuzzy linguistic scale for evaluation

In order to construct the relations between different objects through triangular fuzzy pair comparison matrix, the fuzzy linguistic scale with corresponding triangular fuzzy numbers in the whole paper is selected as Table 1.

Step 3. constructing dependence matrices of value requirements within the same group using rough-fuzzy DEMATEL

Step 3.1. establishing group fuzzy initial direct-relation matrices $\tilde{Z}$

To measure the relationships between n value requirements belonging to a requirement group, a decision group of R decision-makers is invited to make a set of triangular fuzzy pairwise comparison matrices. The fuzzy direct-relation matrix constructed by the sth decision-maker is formed as an $n\times n$ fuzzy matrix $\tilde{Z}_s$ (see Eq. (14)). Elements of $\tilde{Z}_s$ are triangular fuzzy numbers $\tilde{z}_{ij}^s = (l_{ij}^s, m_{ij}^s, u_{ij}^s)$ which represent the degree to which the ith value requirement *VRii* affects the jth value requirement *VRij* within the ith group *VRi*.

$$\tilde{Z}_s = \begin{bmatrix} \tilde{z}_{11}^s & \cdots & \tilde{z}_{1n}^s \\ \vdots & \ddots & \vdots \\ \tilde{z}_{n1}^s & \cdots & \tilde{z}_{nn}^s \end{bmatrix} \tag{14}$$

The group fuzzy initial direct-relation matrix $\tilde{Z}$ can be obtained as follows:

$$\tilde{Z} = \begin{bmatrix} \widehat{z}_{11} & \cdots & \widehat{z}_{1n} \\ \vdots & \ddots & \vdots \\ \widehat{z}_{n1} & \cdots & \widehat{z}_{nn} \end{bmatrix} \tag{15}$$

where $\widehat{z}_{ij} = (\widehat{l}_{ij}, \widehat{m}_{ij}, \widehat{u}_{ij})$, $\widehat{l}_{ij} = \{l_{ij}^1, \ldots, l_{ij}^s, \ldots, l_{ij}^R\}$, $\widehat{m}_{ij} = \{m_{ij}^1, \ldots, m_{ij}^s, \ldots, m_{ij}^R\}$, $\widehat{u}_{ij} = \{u_{ij}^1, \ldots, u_{ij}^s, \ldots, u_{ij}^R\}$.

Step 3.2. Obtaining the rough-fuzzy direct-relation matrices $RN(\tilde{Z})$

Then, the rough number form $RN(l_{ij}^s)$, $RN(m_{ij}^s)$, $RN(u_{ij}^s)$ of l_{ij}^s, m_{ij}^s and u_{ij}^s can be obtained by using Eqs. 6–10, shown as follow:

$$RN\left(l_{ij}^s\right) = \left[\underline{Lim}\left(l_{ij}^s\right), \overline{Lim}\left(l_{ij}^s\right)\right] = \left[l_{ij}^{sL}, l_{ij}^{sU}\right] \tag{16}$$

$$RN\left(m_{ij}^s\right) = \left[\underline{Lim}\left(m_{ij}^s\right), \overline{Lim}\left(m_{ij}^s\right)\right] = \left[m_{ij}^{sL}, m_{ij}^{sU}\right] \tag{17}$$

$$RN\left(u_{ij}^s\right) = \left[\underline{Lim}\left(u_{ij}^s\right), \overline{Lim}\left(u_{ij}^s\right)\right] = \left[u_{ij}^{sL}, u_{ij}^{sU}\right] \tag{18}$$

The rough average number $RN(\widehat{l}_{ij})$, $RN(\widehat{m}_{ij})$ and $RN(\widehat{u}_{ij})$ are obtained as follows:

$$RN\left(\widehat{l}_{ij}\right) = \left[l_{ij}^L, l_{ij}^U\right] = \left[\left(\prod_{s=1}^R l_{ij}^{sL}\right)^{1/R}, \left(\prod_{s=1}^R l_{ij}^{sU}\right)^{1/R}\right] \tag{19}$$

$$RN(\widehat{m}_{ij}) = \left[m_{ij}^L, m_{ij}^U\right] = \left[\left(\prod_{s=1}^R m_{ij}^{sL}\right)^{1/R}, \left(\prod_{s=1}^R m_{ij}^{sU}\right)^{1/R}\right] \tag{20}$$

$$RN(\widehat{u}_{ij}) = \left[u_{ij}^L, u_{ij}^U\right] = \left[\left(\prod_{s=1}^R u_{ij}^{sL}\right)^{1/R}, \left(\prod_{s=1}^R u_{ij}^{sU}\right)^{1/R}\right] \tag{21}$$

Thus, the rough form of triangular fuzzy number $\widehat{z}_{ij}$ can be expressed as follow:

$$RN(\widehat{z}_{ij}) = \left[\widehat{z}_{ij}^L, \widehat{z}_{ij}^U\right] \tag{22}$$

where $\widehat{z}_{ij}^L = (l_{ij}^L, m_{ij}^L, u_{ij}^L)$, $\widehat{z}_{ij}^U = (l_{ij}^U, m_{ij}^U, u_{ij}^U)$.

The rough-fuzzy group initial direct-relation matrix can be then written as:

$$RN\left(\tilde{Z}\right) = \begin{bmatrix} 0 & RN(\widehat{z}_{12}) & \cdots & RN(\widehat{z}_{1n}) \\ RN(\widehat{z}_{21}) & 0 & \cdots & RN(\widehat{z}_{2n}) \\ \vdots & \vdots & \ddots & \vdots \\ RN(\widehat{z}_{n1}) & RN(\widehat{z}_{n2}) & \cdots & 0 \end{bmatrix} \tag{23}$$

Step 3.3. Obtaining normalized rough-fuzzy direct-relation matrix $RN(\tilde{D})$

The normalized rough-fuzzy direct-relation matrix $RN(\tilde{D}) = [RN(\widehat{d}_{ij})]_{n\times n}$ can be obtained by normalizing each matrix element i.e. dividing each element by a rough number $RN(r)$. Using the matrix $RN(\tilde{Z})$ and Eqs. (24) and (25), normalized rough-fuzzy direct-relation matrices $RN(\tilde{D}) = [RN(\widehat{d}_{ij})]_{n\times n}$ is calculated. The element of matrix $RN(\tilde{D})$ is defined as $RN(\widehat{d}_{ij}) = [(d_{ij}^{lL}, d_{ij}^{mL}, d_{ij}^{uL}), (d_{ij}^{lU}, d_{ij}^{mU}, d_{ij}^{uU})]$.

$$RN\left(\widehat{d}_{ij}\right) = \frac{RN(\widehat{z}_{ij})}{RN(r)} \tag{24}$$

$$RN(r) = \left[\max\sum_{j=1}^n u_{ij}^L, \max\sum_{j=1}^n u_{ij}^U\right], \quad i,j\in\{1,2,\ldots,n\} \tag{25}$$

Thus, $RN(\widehat{d}_{ij})$ can be written as:

$$RN\left(\widehat{d}_{ij}\right) = \left[\left(\frac{l_{ij}^L}{\max\sum_{j=1}^n u_{ij}^L}, \frac{m_{ij}^L}{\max\sum_{j=1}^n u_{ij}^L}, \frac{u_{ij}^L}{\max\sum_{j=1}^n u_{ij}^L}\right), \left(\frac{l_{ij}^U}{\max\sum_{j=1}^n u_{ij}^U}, \frac{m_{ij}^U}{\max\sum_{j=1}^n u_{ij}^U}, \frac{u_{ij}^U}{\max\sum_{j=1}^n u_{ij}^U}\right)\right] \tag{26}$$

Step 3.4. Acquiring rough-fuzzy total direction matrices $RN(\tilde{T})$

The six crisp matrices $D_{lL} = [d_{ij}^{lL}]_{n\times n}$, $D_{lU} = [d_{ij}^{lU}]_{n\times n}$, $D_{mL} = [d_{ij}^{mL}]_{n\times n}$, $D_{mU} = [d_{ij}^{mU}]_{n\times n}$, $D_{uL} = [d_{ij}^{uL}]_{n\times n}$ and $D_{uU} = [d_{ij}^{uU}]_{n\times n}$ whose elements are extracted from matrix $RN(\tilde{D})$. The matrix D_{lL} and D_{lU} are defined as follow examples:

The rough-fuzzy total direction matrix $RN(\tilde{T})$ is obtained using the following equation:

$$RN\left(\tilde{T}\right) = RN\left(\tilde{D}\right)\left(I - RN\left(\tilde{D}\right)\right)^{-1} \tag{27}$$

Let $RN(\tilde{T}) = [RN(\widehat{t}_{ij})]_{n\times n}$, where $RN(\widehat{t}_{ij}) = [(t_{ij}^{lL}, t_{ij}^{mL}, t_{ij}^{uL}), (t_{ij}^{lU}, t_{ij}^{mU}, t_{ij}^{uU})]$, then:

$$T_{lL} = \left[t_{ij}^{lL}\right]_{n\times n} = D_{lL}(I - D_{lL})^{-1} \tag{28}$$

$$T_{lU} = \left[t_{ij}^{lU}\right]_{n\times n} = D_{lU}(I - D_{lU})^{-1} \tag{29}$$

Similarly, the matrices $T_{mL} = [t_{ij}^{mL}]_{n\times n}$, $T_{mU} = [t_{ij}^{mU}]_{n\times n}$, $T_{uL} = [t_{ij}^{uL}]_{n\times n}$ and $T_{uU} = [t_{ij}^{uU}]_{n\times n}$ can be acquired applying the Eq. (27)~(29).

Step 3.5. Forming rough dependence matrices RN(T)

Aiming to acquire the value of dependence matrices of value requirements within the same group, it is necessary to defuzzyfy the elements of rough-fuzzy total direction matrices. Let $RN(T) = [RN(t_{ij})]_{n\times n}$, where $RN(\widehat{t}_{ij}) = [t_{ij}^{L}, t_{ij}^{U}]$, then t_{ij}^{L} and t_{ij}^{U} can be calculated as follows (Kutlu and Ekmekçioğ;lu, 2012):

$$t_{ij}^{L} = \frac{t_{ij}^{lL} + 4t_{ij}^{mL} + t_{ij}^{uL}}{6} \tag{30}$$

$$t_{ij}^{U} = \frac{t_{ij}^{lU} + 4t_{ij}^{mU} + t_{ij}^{uU}}{6} \tag{31}$$

Step 3.6. Obtaining the normalized dependence matrix TN

Let $T = [t_{ij}]_{n\times n}$, where the element t_{ij} is taken the crisp value of element of $RN(T)$. The element is calculated as follow:

$$t_{ij} = (1 - \lambda_{ij})t_{ij}^{L} + \lambda_{ij}t_{ij}^{U}, \qquad 0 < \lambda_{ij} < 1 \tag{32}$$

where λ_{ij} denotes the optimistic indicator which is introduced to transform the rough weight $RN(t_{ij}) = [t_{ij}^{L}, t_{ij}^{U}]$ to crisp value t_{ij}. According to Song et al. (2013), if decision-makers are more optimistic about their judgements, then λ_{ij} can select a bigger value ($\lambda_{ij} > 0.5$). If decision-makers keep a moderate attribute, i.e. neither more optimistic nor more pessimistic, λ_{ij} select a certain value 0.5.

To form the final supermatrix in the last step of this model, each element in the matrix T is required to be normalized by the sum of related column. Then the normalized dependence matrix T_N is obtained for the inputs to create the initial supermatrix.

Step 4. constructing dependence matrices of value requirements among different groups using rough-fuzzy ANP

Step 4.1. Building fuzzy pair-wise judgement matrix $\tilde{A}_k$ of the kth decision-maker who is included in an m members' team

This matrix is formed to pairwise compare the relative importance of the value requirements within the ith group towards the value requirements belonging to the jth ($i \neq j$) group using the ANP method. The triangular fuzzy number is in utilization of evaluating the preference of each value requirement in relation to other value requirements.

The fuzzy judgement matrix $\tilde{A}_k$ is established as follow:

$$\tilde{A}_k = \begin{bmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & 1 \end{bmatrix} \tag{33}$$

where $\tilde{a}_{ij}^{k} = (l_{ij}^{k}, m_{ij}^{k}, u_{ij}^{k})$, $i = j = 1, 2, \ldots, n$; $\tilde{a}_{ij}^{k} = (\tilde{a}_{ji}^{k})^{-1} = \left(\frac{1}{u_{ji}^{k}}, \frac{1}{m_{ji}^{k}}, \frac{1}{l_{ji}^{k}}\right)$; n denotes the number of objects.

The consistency of the triangular fuzzy pair-wise judgement matrix is checked by using the examination method proposed by (Gogus and Boucher, 1998). This method provided a convenient operation to revise the unqualified matrix (Valipour Parkouhi and Safaei Ghadikolaei, 2017). Since this paper dose not discuss much about the consistency examination, the interested readers are encouraged to check the corresponding reference for more information.

Step 4.2. Building rough-fuzzy pair-wise judgement matrix $RN(\tilde{A})$

Since the element $\tilde{a}_{ij}^{k} = (\tilde{a}_{ji}^{k})^{-1} = \left(\frac{1}{u_{ji}^{k}}, \frac{1}{m_{ji}^{k}}, \frac{1}{l_{ji}^{k}}\right)$, in order to describe the below procedures more conveniently, the upper triangular matrix of the judgement matrix is only considered in this section. After consistency examination of each pair-wise judgement matrix, the group fuzzy judgement matrix $\tilde{A}$ can be then built as follows:

$$\tilde{A} = \begin{bmatrix} 1 & \widehat{a}_{12} & \cdots & \widehat{a}_{1n} \\ & 1 & \cdots & \widehat{a}_{2n} \\ & & \ddots & \vdots \\ & & & 1 \end{bmatrix} \tag{34}$$

where $i \le j$, $\widehat{a}_{ij} = (\widehat{l}_{ij}^{a}, \widehat{m}_{ij}^{a}, \widehat{u}_{ij}^{a})$, $\widehat{l}_{ij}^{a} = \{l_{ij}^{1}, \ldots, l_{ij}^{k}, \ldots, l_{ij}^{m}\}$, $\widehat{m}_{ij}^{a} = \{m_{ij}^{1}, \ldots, m_{ij}^{k}, \ldots, m_{ij}^{m}\}$, $\widehat{u}_{ij}^{a} = \{u_{ij}^{1}, \ldots, u_{ij}^{k}, \ldots, u_{ij}^{m}\}$.

The rough average number of triangular fuzzy number $\widehat{a}_{ij}$ can be expressed as follow by using Eq. (17)~(26):

$$RN(\widehat{a}_{ij}) = \left[\widehat{a}_{ij}^{L}, \widehat{a}_{ij}^{U}\right] \tag{35}$$

where $\widehat{a}_{ij}^{L} = (l_{ij}^{aL}, m_{ij}^{aL}, u_{ij}^{aL})$, $\widehat{a}_{ij}^{U} = (l_{ij}^{aU}, m_{ij}^{aU}, u_{ij}^{aU})$.

The rough-fuzzy group pair-wise judgement matrix $RN(\tilde{A})$ can be then written as:

$$RN\left(\tilde{A}\right) = \begin{bmatrix} 1 & RN(\widehat{a}_{12}) & \cdots & RN(\widehat{a}_{1n}) \\ & 1 & \cdots & RN(\widehat{a}_{2n}) \\ & & \ddots & \vdots \\ & & & 1 \end{bmatrix} \tag{36}$$

Step 4.3. Acquiring rough priority vector $RN(W)$ of rough-fuzzy pair-wise judgement matrix $RN(\tilde{A})$ using LFPP method

The rough form of priority vector of the group pair-wise judgement matrix can be represented as $RN(W) = [W^{L}, W^{U}]$, where:

$$W^L = \left(w_1^L, \ldots, w_i^L, \ldots, w_n^L\right)^T, \qquad \sum_{i=1}^{n} w_i^L = 1 \tag{37}$$

$$W^U = \left(w_1^U, \ldots, w_i^U, \ldots, w_n^U\right)^T, \qquad \sum_{i=1}^{n} w_i^U = 1 \tag{38}$$

To obtain the W^L and W^U, the two fuzzy matrices $\tilde{A}^L$ and $\tilde{A}^U$ whose elements are extracted from the matrix $RN(\tilde{A})$ are formed as follows:

$$\tilde{A}^L = \begin{bmatrix} 1 & \hat{a}_{12}^L & \cdots & \hat{a}_{1n}^L \\ & 1 & \cdots & \hat{a}_{2n}^L \\ & & \ddots & \vdots \\ & & & 1 \end{bmatrix}, \quad \tilde{A}^U = \begin{bmatrix} 1 & \hat{a}_{12}^U & \cdots & \hat{a}_{1n}^U \\ & 1 & \cdots & \hat{a}_{2n}^U \\ & & \ddots & \vdots \\ & & & 1 \end{bmatrix} \tag{39}$$

The priority vector can be obtained from the matrix using various methods and in this paper the "logarithmic fuzzy preference programming" (LFPP) (Wang and Chin, 2011) method is adopted. The LFPP is adopted to acquire the priority vector from the rough-fuzzy comparison matrix in which retains the triangular fuzzy characteristics. The effectiveness and accuracy of LFPP method has been proved by many researchers, especially for obtaining the unique crisp normalized optimal priority vector (Alikhani and Azar, 2015; An et al., 2018; Ge et al., 2017). The following model (40) is introduced as an example to obtain crisp the priority vector W^L, and also W^U can be calculated by the similar operation. The values of the deviation variables are required to be as small as possible.

$$\begin{aligned} &\text{Minimize} \quad J \\ &J = \left(1-\lambda^L\right)^2 + M \cdot \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \left(\left(\delta_{ij}^L\right)^2 + \left(\eta_{ij}^L\right)^2\right) \\ &s.t. \begin{cases} x_i^L - x_j^L - \lambda^L \ln\left(m_{ij}^{aL} \big/ l_{ij}^{aL}\right) + \delta_{ij}^L \geq \ln l_{ij}^{aL}, i = 1, \ldots, n-1; j = i+1, \ldots, n, \\ -x_i^L + x_j^L - \lambda^L \ln\left(u_{ij}^{aL} \big/ m_{ij}^{aL}\right) + \eta_{ij}^L \geq -\ln u_{ij}^{aL}, i = 1, \ldots, n-1; j = i+1, \ldots, n, \\ \lambda^L, x_i^L \geq 0, i = 1, \ldots, n, \\ \delta_{ij}^L, \eta_{ij}^L \geq 0, i = 1, \ldots, n-1; j = i+1, \ldots, n, \end{cases} \end{aligned} \tag{40}$$

where $x_i^L = \ln w_i^L$ for $i = 1,\ldots,n$ and M is a specified sufficiently large constant such as $M = 10000$. δ_{ij}^L and η_{ij}^L denote the deviation variables which are introduced to avoid λ^L from taking a negative value.

Let $x_i^{L*} (i = 1, \ldots, n)$ be the optimal solution to model (40). The normalized priorities for fuzzy pairwise comparison matrix $\tilde{A}^L$ can be obtained as follow:

$$w_i^{L*} = \frac{e^{x_i^{L*}}}{\sum_{1 \leq i \leq n} e^{x_i^{L*}}} \tag{41}$$

where e is the base of natural logarithm.

Similarly, applying the model (40) and Eq. (41), the normalized priorities w_i^{U*} for fuzzy pairwise comparison matrix $\tilde{A}^U$ can be obtained.

Step 4.4. Acquiring dependence matrices W_{ij} $(i \neq j)$ of value requirements among different groups

Convert the normalized rough priority vector $RN(W) = [W^L, W^U]$ to crisp normalized priority vector W^N. The element w_i^N of the vector W^N can be calculated as follow:

$$w_i^N = (1-\beta) w_i^{L*} + \beta w_i^{U*} \tag{42}$$

where β denotes the optimistic indicator.

The element of dependence matrices W_{ij} is represented as w_{ij} which denotes the influential strength of the ith value requirement VR_{ii} within the ith group VR_i on the jth value requirement VR_{jj} within jth group VR_j. The column of W_{ij} is taken as the corresponding priority vector W^N.

Step 5. obtaining the priority of each value requirement

Step 5.1. Forming initial supermatrix W_I by combining the dependence matrices of VRs within and among groups. The relations among all groups are calculated through the procedures above, afterwards they will be integrated into the corresponding position to form a supermatrix as shown in Fig. 5

Step 5.2. Obtaining the normalized weighted supermatrix W_{NW}. First, by multiplying the initial supermatrix W_I and the dependences matrix of different VR groups T_N^g which is obtained by using rough-fuzzy DEMATEL method proposed in Step 3, the weighted supermatrix W_W is informed by follows

$$W_W = W_I \times T_N^g = \begin{bmatrix} T_N^1 \times t_{N11}^g & \cdots & W_{1i} \times t_{N1i}^g & \cdots & W_{1n} \times t_{N1n}^g \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ W_{i1} \times t_{Ni1}^g & \cdots & T_N^i \times t_{Nii}^g & \cdots & W_{in} \times t_{Nin}^g \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ W_{n1} \times t_{Nn1}^g & \cdots & W_{ni} \times t_{Nni}^g & \cdots & W_{nn} \times t_{Nnn}^g \end{bmatrix} \tag{43}$$

where t_{Nij}^g is the element of dependences matrix T_N^g.

Then, the weighted matrix supermatrix W_W is normalized by the sum of related column, thus the normalized weighted supermatrix W_{NW} is informed.

Step 5.3. Obtaining the limit supermatrix W by raising the normalized weighted supermatrix to the limiting powers. The limit supermatrix W is acquired by using Eq. (44) (Thomas L, 2013)

$$W = \lim_{m \to \infty} W_{NW}^{2m+1} \tag{44}$$

$$W_I = \begin{array}{cc} & \begin{array}{ccccc} VR_1 & \cdots & VR_i & \cdots & VR_n \\ VR_{11}\cdots VR_{1n_1} & & VR_{i1}\cdots VR_{in_i} & & VR_{n1}\cdots VR_{nn_n} \end{array} \\ \begin{array}{cc} & VR_{11} \\ VR_1 & \vdots \\ & VR_{1n_1} \\ \vdots & \\ & VR_{i1} \\ VR_i & \vdots \\ & VR_{in_i} \\ \vdots & \\ & VR_{n1} \\ VR_n & \vdots \\ & VR_{nn_n} \end{array} & \begin{bmatrix} T_N^1 & \cdots & W_{1i} & \cdots & W_{1n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ W_{i1} & \cdots & T_N^i & \cdots & W_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ W_{n1} & \cdots & W_{ni} & \cdots & T_N^n \end{bmatrix} \end{array}$$

Fig. 5. Supermatrix of relations among value requirements.

where m is one of the numbers in the set of natural numbers and its value is sufficiently large so that the matrix is converged. The row values of the matrix for each column are converging to the same values which denote the final weight of the value requirement.

4. Case study

4.1. Background of case study

In this section, sustainable value requirement elicitation and evaluation of an excavator in the context of smart product service system is taken as an example to demonstrate the application of the proposed approach in real industry. Owing to the remarkable development of emerging technologies such as intelligent sensing, big data, cloud computation, internet of things, industrial internet, artificial intelligence e.g., the manufacturing industry has entered the era of intelligent. Many traditional PSS suppliers have strived to offer smart products and services to meet the sustainable value requirements of customers. A smart PSS that connect to the Internet during operation will form the basis of a whole range of new data- and service-based business models. This kind of PSS can fulfill customer requirement automatically and intelligently. In this case, the excavator is mainly designed and sold to the mining camps that need the qualified and intelligent excavator to complete complex digging work. Excavator Manufacturer A is a Fortune 500 manufacture who is specialized in providing different excavators and related services for industry: mining industry, construction industry, shipbuilding industry, metallurgical industry and any other industries in which the excavator is applied. The company A now is more and more concerned with selling sustainable industrial services based on the Industrial Internet Platform developed by itself in which the sold excavators are networked and perceived. This platform makes it possible to collect large quantities of data from the use life of individual excavator and use them as a basis for delivering sustainable value to the customers. The objective of the sustainable requirement evaluation in this case study is to identify key points that the customer is concerned for further sustainable PSS design, and therefore, enhance the sustainability, customer satisfaction and loyalty. The comparisons among fuzzy approach-based, rough approach-based and the proposed rough-fuzzy approach-based DEMATEL-ANP method; comparisons among fuzzy, rough and the proposed rough-fuzzy interval; comparisons among the proposed rough-fuzzy DEMATEL, the fuzzy DEMATEL, and the rough DEMATEL; comparisons among fuzzy approach-based, rough approach-based and the proposed rough-fuzzy approach-based pair-wise comparison method; are conducted to reveal the advantages of the proposed methodology.

4.2. Elicitation of sustainable value requirement of smart excavator PSS

A survey based on PVSM is used to analyze the value proposition of each value state of an excavator. The value requirements in accordance with each value proposition are categorized into five groups, namely VR1: Optimization of excavator's running, VR2: Quick correction of excavator's stoppage, VR3: Sharing to other users of excavator's idle value, VR4: Accurate maintenance of excavator's deterioration and VR5: Reuse of excavator's waste components or system. Belonged to each group, there are detailed value requirements as follows:

VR1: Optimization of excavator's running
- VR11: Optimization of the running way of the excavator
- VR12: Reduction of energy consumption for the running of the excavator
- VR13: Improvement of the excavator's capacity utilization
- VR14: Improvement of the excavator's capacity throughput

VR2: Quick correction of excavator's stoppage
- VR21: Remote monitoring the excavator by connecting it into the monitoring platform
- VR22: Fault diagnosis using data-based analysis of the excavator status
- VR23: Timely repair based on the fast support provided by the manufacturer
- VR24: Obtaining the spare parts quickly with the real-time spare parts distribution

VR3: Sharing to other users of excavator's idle value
- VR31: Sharing a full set of solutions for mining operation to other users
- VR32: Sharing the idle operator and excavator to other users
- VR33: Sharing the idle excavator to other users

VR4: Accurate maintenance of excavator's deterioration
- VR41: Proactive maintenance for preventing certain unscheduled stoppages of excavator
- VR42: Health management for keeping the excavator in a healthy status
- VR43: Parts updating for keeping the excavator with a normal performance
- VR44: Function upgradation for providing the old excavator with newly value added function

VR5: Reuse of excavator's waste components or system
- VR51: Second-hand exchange of waste parts of the excavator
- VR52: Remanufacturing the key or expensive parts of the excavator
- VR53: Reverse logistics for transporting the waste parts or excavator back to manufacturer
- VR54: Disassembling the waste excavator to recover useful components

4.3. Evaluation of sustainable value requirement of smart excavator PSS

The rough-fuzzy DEMATEL-ANP model described in Section 3.2 is applied for prioritizing the sustainable value requirement of smart excavator PSS. Evaluation of value requirements within the same groups and among different groups are performed by a decision team (expert team) which is consisting of 5 DMs: 2 customer representatives, 2 designers and 1 manager. The two customer representatives are senior procurement engineer and experienced end user who are both from the most important customer company. Both of them have the deepest understanding on the actual value requirement for excavator PSS. The two designers are excavator designer and excavator service designer who have more than 8 years' experience in their own domains. The manager has been responsible for developing and operating the excavator PSS project for more than 5 years. In addition to selecting the representative experts, several efforts have been made, e.g. training the members for making actual judgement, and keeping independent decision environment, etc. in order to ensure the quality of the data collected from the expert team. The combination of multiple DMs can increase the decision comprehensiveness and reduce the risk of misjudgement. These DMs are numbered by DM1~5 respectively.

As for the value requirements evaluation structure shown in Fig. 4, firstly the relative importance of value requirement within the value requirement group should be established using the rough-fuzzy DEMATEL method (Step 3). For each value requirement group, the group fuzzy direct-relation matrices are formed (Step 3.1). Fuzzy scores are obtained by converting the linguistic evaluations of DMs using the relations given in Table 1. The example of group fuzzy direct-relation matrix of VR1: Optimization of excavator's running is shown as follows:

$$\tilde{Z}=\begin{bmatrix}
\begin{pmatrix}\{0.0,0.0,0.0,0.0,0.0\},\\ \{0.0,0.0,0.0,0.0,0.0\},\\ \{0.0,0.0,0.0,0.0,0.0\}\end{pmatrix} & \begin{pmatrix}\{3.0,3.0,6.0,5.0,2.0\},\\ \{4.0,4.0,7.0,6.0,3.0\},\\ \{5.0,5.0,8.0,7.0,4.0\}\end{pmatrix} & \begin{pmatrix}\{5.0,3.0,3.0,6.0,1.0\},\\ \{6.0,4.0,4.0,7.0,2.0\},\\ \{7.0,5.0,5.0,8.0,3.0\}\end{pmatrix} & \begin{pmatrix}\{0.1,2.0,1.0,1.0,0.1\},\\ \{0.1,3.0,2.0,2.0,1.0\},\\ \{1.0,4.0,3.0,3.0,2.0\}\end{pmatrix}\\
\begin{pmatrix}\{0.1,0.1,2.0,6.0,2.0\},\\ \{1.0,1.0,3.0,7.0,3.0\},\\ \{2.0,2.0,4.0,8.0,4.0\}\end{pmatrix} & \begin{pmatrix}\{0.0,0.0,0.0,0.0,0.0\},\\ \{0.0,0.0,0.0,0.0,0.0\},\\ \{0.0,0.0,0.0,0.0,0.0\}\end{pmatrix} & \begin{pmatrix}\{6.0,6.0,6.0,6.0,6.0\},\\ \{7.0,7.0,7.0,7.0,7.0\},\\ \{8.0,8.0,8.0,8.0,8.0\}\end{pmatrix} & \begin{pmatrix}\{0.1,1.0,1.0,1.0,1.0\},\\ \{0.1,2.0,2.0,2.0,2.0\},\\ \{1.0,3.0,3.0,3.0,3.0\}\end{pmatrix}\\
\begin{pmatrix}\{0.1,0.1,2.0,1.0,1.0\},\\ \{1.0,1.0,3.0,2.0,2.0\},\\ \{2.0,2.0,4.0,3.0,3.0\}\end{pmatrix} & \begin{pmatrix}\{2.0,2.0,2.0,2.0,2.0\},\\ \{3.0,3.0,3.0,3.0,3.0\},\\ \{4.0,4.0,4.0,4.0,4.0\}\end{pmatrix} & \begin{pmatrix}\{0.0,0.0,0.0,0.0,0.0\},\\ \{0.0,0.0,0.0,0.0,0.0\},\\ \{0.0,0.0,0.0,0.0,0.0\}\end{pmatrix} & \begin{pmatrix}\{0.1,0.1,3.0,3.0,3.0\},\\ \{0.1,0.1,4.0,4.0,4.0\},\\ \{1.0,1.0,5.0,5.0,5.0\}\end{pmatrix}\\
\begin{pmatrix}(1.0,2.0,2.0,4.0,2.0\},\\ \{2.0,3.0,3.0,5.0,3.0\},\\ \{3.0,4.0,4.0,6.0,4.0\}\end{pmatrix} & \begin{pmatrix}\{4.0,4.0,7.0,4.0,4.0\},\\ \{5.0,5.0,8.0,5.0,5.0\},\\ \{6.0,6.0,9.0,6.0,6.0\}\end{pmatrix} & \begin{pmatrix}\{3.0,4.0,4.0,2.0,4.0\},\\ \{4.0,5.0,5.0,3.0,5.0\},\\ \{5.0,6.0,6.0,4.0,6.0\}\end{pmatrix} & \begin{pmatrix}\{0.0,0.0,0.0,0.0,0.0\},\\ \{0.0,0.0,0.0,0.0,0.0\},\\ \{0.0,0.0,0.0,0.0,0.0\}\end{pmatrix}
\end{bmatrix}$$

The next step is the formation of rough-fuzzy direct-relation matrices (Step 3.2) for each value requirement group. These matrices are obtained from the group fuzzy direct-relation matrices using the rough set method (Eq. (16)~(23)). The detailed operation for transforming the group decision to rough number is explained by taking example of $\widehat{m}_{12}=\{4,4,7,6,3\}$ shown in the group fuzzy direct-relation matrix. The rough number form for each element can be obtained using Eq. (6)~(10), and the rough average number $RN(\widehat{m}_{12})$ is acquired using Eq. (20) as follows:

$$\underline{Lim}(3)=3\quad \overline{Lim}(3)=\sqrt[5]{3\times4\times4\times6\times7}=4.580$$

$$\underline{Lim}(4)=\sqrt[3]{3\times4\times4}=3.634\quad \overline{Lim}(4)=\sqrt[4]{4\times4\times6\times7}=5.092$$

$$\underline{Lim}(6)=\sqrt[4]{3\times4\times4\times6}=4.120\quad \overline{Lim}(6)=\sqrt[2]{6\times7}=6.481$$

$$\underline{Lim}(7)=\sqrt[5]{3\times4\times4\times6\times7}=4.580\quad \overline{Lim}(7)=7$$

$$RN\left(m_{12}^{1}\right)=RN\left(m_{12}^{2}\right)=\left[\underline{Lim}(4),\overline{Lim}(4)\right]=[3.634,5.092]$$

$$RN\left(m_{12}^{3}\right)=\left[\underline{Lim}(6),\overline{Lim}(6)\right]=[4.120,6.481]$$

$$RN\left(m_{12}^{4}\right)=\left[\underline{Lim}(7),\overline{Lim}(7)\right]=[4.580,7]$$

$$RN\left(m_{12}^{5}\right)=\left[\underline{Lim}(3),\overline{Lim}(3)\right]=[3,4.580]$$

$$RN(\widehat{m}_{12})=\left[m_{12}^{L},m_{12}^{U}\right]=[3.756,5.572]$$

Similarly, the rough average number of each element of rough-fuzzy direct-relation matrix of each value requirement group is obtained by using same procedure. The rough-fuzzy direct-relation matrix of the group VR1 is shown as follows:

$$RN\left(\tilde{Z}\right)=\begin{bmatrix}
\begin{bmatrix}(0.000,0.000,0.000),\\ (0.000,0.000,0.000)\end{bmatrix} & \begin{bmatrix}(2.720,3.756,4.778),\\ (4.527,5.572,6.607)\end{bmatrix} & \begin{bmatrix}(2.028,3.163,4.230),\\ (4.403,5.486,6.531)\end{bmatrix} & \begin{bmatrix}(0.215,0.461,1.698),\\ (0.921,1.979,3.127)\end{bmatrix}\\
\begin{bmatrix}(0.273,1.470,2.567),\\ (1.950,3.572,4.768)\end{bmatrix} & \begin{bmatrix}(0.000,0.000,0.000),\\ (0.000,0.000,0.000)\end{bmatrix} & \begin{bmatrix}(6.000,7.000,8.000),\\ (6.000,7.000,8.000)\end{bmatrix} & \begin{bmatrix}(0.437,0.680,2.020),\\ (0.912,1.774,2.871)\end{bmatrix}\\
\begin{bmatrix}(0.215,1.269,2.303),\\ (0.921,2.117,3.167)\end{bmatrix} & \begin{bmatrix}(2.000,3.000,4.000),\\ (2.000,3.000,4.000)\end{bmatrix} & \begin{bmatrix}(0.000,0.000,0.000),\\ (0.000,0.000,0.000)\end{bmatrix} & \begin{bmatrix}(0.340,0.373,1.785),\\ (1.741,2.212,3.865)\end{bmatrix}\\
\begin{bmatrix}(1.569,2.614,3.634),\\ (2.549,3.603,4.632)\end{bmatrix} & \begin{bmatrix}(4.091,5.095,6.098),\\ (4.893,5.922,6.943)\end{bmatrix} & \begin{bmatrix}(2.806,3.841,4.862),\\ (3.791,4.802,5.807)\end{bmatrix} & \begin{bmatrix}(0.000,0.000,0.000),\\ (0.000,0.000,0.000)\end{bmatrix}
\end{bmatrix}$$

Furthermore, form the normalized rough-fuzzy direct-relation matrices for each value requirement group (Step 3.3). Those matrices are formed by applying Eq. (26). The normalized rough-fuzzy direct-relation matrix of the group VR1 is shown as follows:

$$RN\left(\tilde{D}\right)=\begin{bmatrix}
\begin{bmatrix}(0.000,0.000,0.000),\\(0.000,0.000,0.000)\end{bmatrix} & \begin{bmatrix}(0.159,0.220,0.280),\\(0.223,0.274,0.325)\end{bmatrix} & \begin{bmatrix}(0.119,0.185,0.248),\\(0.217,0.270,0.321)\end{bmatrix} & \begin{bmatrix}(0.013,0.027,0.099),\\(0.045,0.097,0.154)\end{bmatrix}\\
\begin{bmatrix}(0.016,0.086,0.150),\\(0.096,0.176,0.234)\end{bmatrix} & \begin{bmatrix}(0.000,0.000,0.000),\\(0.000,0.000,0.000)\end{bmatrix} & \begin{bmatrix}(0.351,0.410,0.468),\\(0.295,0.344,0.393)\end{bmatrix} & \begin{bmatrix}(0.026,0.040,0.118),\\(0.045,0.087,0.141)\end{bmatrix}\\
\begin{bmatrix}(0.013,0.074,0.135),\\(0.045,0.104,0.156)\end{bmatrix} & \begin{bmatrix}(0.117,0.176,0.234),\\(0.098,0.148,0.197)\end{bmatrix} & \begin{bmatrix}(0.000,0.000,0.000),\\(0.000,0.000,0.000)\end{bmatrix} & \begin{bmatrix}(0.020,0.022,0.104),\\(0.086,0.109,0.190)\end{bmatrix}\\
\begin{bmatrix}(0.092,0.153,0.213),\\(0.125,0.177,0.228)\end{bmatrix} & \begin{bmatrix}(0.239,0.298,0.357),\\(0.241,0.291,0.341)\end{bmatrix} & \begin{bmatrix}(0.164,0.225,0.284),\\(0.186,0.236,0.286)\end{bmatrix} & \begin{bmatrix}(0.000,0.000,0.000),\\(0.000,0.000,0.000)\end{bmatrix}
\end{bmatrix}$$

By applying the Eq. (27) on the normalized rough-fuzzy direct-relation matrices, the rough-fuzzy total direct-relation matrices are obtained. The rough-fuzzy total direct-relation matrices of the VRs within each VR group and of the VR groups are respectively shown as follows:

Rough-fuzzy total direction relation matrix of VR11-VR14 within the group VR1:

$$RN\left(\tilde{T}_1\right)=\begin{bmatrix}
\begin{bmatrix}(0.007,0.058,0.232),\\(0.054,0.173,0.465)\end{bmatrix} & \begin{bmatrix}(0.188,0.305,0.591),\\(0.288,0.461,0.842)\end{bmatrix} & \begin{bmatrix}(0.189,0.332,0.656),\\(0.330,0.525,0.952)\end{bmatrix} & \begin{bmatrix}(0.021,0.048,0.261),\\(0.089,0.212,0.525)\end{bmatrix}\\
\begin{bmatrix}(0.025,0.145,0.387),\\(0.131,0.307,0.630)\end{bmatrix} & \begin{bmatrix}(0.057,0.139,0.409),\\(0.086,0.222,0.564)\end{bmatrix} & \begin{bmatrix}(0.380,0.507,0.838),\\(0.365,0.550,0.961)\end{bmatrix} & \begin{bmatrix}(0.035,0.060,0.292),\\(0.086,0.196,0.500)\end{bmatrix}\\
\begin{bmatrix}(0.018,0.109,0.308),\\(0.076,0.205,0.483)\end{bmatrix} & \begin{bmatrix}(0.132,0.232,0.490),\\(0.148,0.283,0.610)\end{bmatrix} & \begin{bmatrix}(0.052,0.123,0.371),\\(0.079,0.194,0.523)\end{bmatrix} & \begin{bmatrix}(0.025,0.037,0.232),\\(0.102,0.175,0.500)\end{bmatrix}\\
\begin{bmatrix}(0.101,0.230,0.488),\\(0.178,0.345,0.687)\end{bmatrix} & \begin{bmatrix}(0.292,0.438,0.768),\\(0.325,0.504,0.900)\end{bmatrix} & \begin{bmatrix}(0.281,0.454,0.829),\\(0.330,0.535,0.980)\end{bmatrix} & \begin{bmatrix}(0.014,0.034,0.226),\\(0.051,0.136,0.419)\end{bmatrix}
\end{bmatrix}$$

Rough-fuzzy total direction relation matrix of VR21-VR24 within the group VR2:

$$RN\left(\tilde{T}_2\right)=\begin{bmatrix}
\begin{bmatrix}(0.008,0.105,0.449),\\(0.064,0.256,0.839)\end{bmatrix} & \begin{bmatrix}(0.189,0.385,0.895),\\(0.270,0.539,1.264)\end{bmatrix} & \begin{bmatrix}(0.159,0.376,0.921),\\(0.285,0.573,1.348)\end{bmatrix} & \begin{bmatrix}(0.022,0.175,0.552),\\(0.127,0.379,0.997)\end{bmatrix}\\
\begin{bmatrix}(0.027,0.202,0.618),\\(0.157,0.423,1.066)\end{bmatrix} & \begin{bmatrix}(0.052,0.208,0.693),\\(0.108,0.350,1.061)\end{bmatrix} & \begin{bmatrix}(0.309,0.515,1.064),\\(0.383,0.670,1.456)\end{bmatrix} & \begin{bmatrix}(0.023,0.181,0.571),\\(0.121,0.376,1.009)\end{bmatrix}\\
\begin{bmatrix}(0.021,0.173,0.548),\\(0.099,0.319,0.878)\end{bmatrix} & \begin{bmatrix}(0.154,0.341,0.821),\\(0.183,0.429,1.080)\end{bmatrix} & \begin{bmatrix}(0.051,0.197,0.660),\\(0.100,0.319,0.975)\end{bmatrix} & \begin{bmatrix}(0.025,0.177,0.532),\\(0.146,0.375,0.923)\end{bmatrix}\\
\begin{bmatrix}(0.127,0.315,0.787),\\(0.247,0.518,1.234)\end{bmatrix} & \begin{bmatrix}(0.288,0.523,1.132),\\(0.423,0.722,1.552)\end{bmatrix} & \begin{bmatrix}(0.281,0.530,1.176),\\(0.380,0.703,1.593)\end{bmatrix} & \begin{bmatrix}(0.012,0.133,0.530),\\(0.087,0.316,0.987)\end{bmatrix}
\end{bmatrix}$$

Rough-fuzzy total direction relation matrix of VR31-VR33 within the group VR3:

$$RN\left(\tilde{T}_3\right)=\begin{bmatrix}
\begin{bmatrix}(0.014,0.159,0.652),\\(0.092,0.341,1.042)\end{bmatrix} & \begin{bmatrix}(0.280,0.548,1.242),\\(0.401,0.741,1.619)\end{bmatrix} & \begin{bmatrix}(0.269,0.591,1.392),\\(0.437,0.819,1.793)\end{bmatrix}\\
\begin{bmatrix}(0.040,0.294,0.884),\\(0.223,0.583,1.390)\end{bmatrix} & \begin{bmatrix}(0.078,0.298,0.967),\\(0.198,0.524,1.421)\end{bmatrix} & \begin{bmatrix}(0.464,0.765,1.571),\\(0.571,0.969,1.996)\end{bmatrix}\\
\begin{bmatrix}(0.028,0.226,0.711),\\(0.132,0.413,1.075)\end{bmatrix} & \begin{bmatrix}(0.166,0.407,1.010),\\(0.318,0.624,1.396)\end{bmatrix} & \begin{bmatrix}(0.075,0.274,0.901),\\(0.169,0.454,1.264)\end{bmatrix}
\end{bmatrix}$$

Rough-fuzzy total direction relation matrix of VR41-VR44 within the group VR4:

$$RN\left(\tilde{T}_4\right)=\begin{bmatrix}
\begin{bmatrix}(0.017,0.161,0.721),\\(0.133,0.396,1.258)\end{bmatrix} & \begin{bmatrix}(0.159,0.397,1.109),\\(0.323,0.651,1.635)\end{bmatrix} & \begin{bmatrix}(0.197,0.450,1.197),\\(0.399,0.735,1.759)\end{bmatrix} & \begin{bmatrix}(0.042,0.237,0.783),\\(0.205,0.488,1.295)\end{bmatrix}\\
\begin{bmatrix}(0.064,0.295,0.896),\\(0.338,0.657,1.571)\end{bmatrix} & \begin{bmatrix}(0.033,0.204,0.843),\\(0.168,0.470,1.444)\end{bmatrix} & \begin{bmatrix}(0.181,0.425,1.148),\\(0.402,0.751,1.798)\end{bmatrix} & \begin{bmatrix}(0.023,0.200,0.728),\\(0.152,0.451,1.280)\end{bmatrix}\\
\begin{bmatrix}(0.026,0.208,0.743),\\(0.141,0.415,1.193)\end{bmatrix} & \begin{bmatrix}(0.119,0.325,0.943),\\(0.250,0.540,1.390)\end{bmatrix} & \begin{bmatrix}(0.028,0.185,0.783),\\(0.126,0.387,1.240)\end{bmatrix} & \begin{bmatrix}(0.026,0.194,0.669),\\(0.156,0.415,1.111)\end{bmatrix}\\
\begin{bmatrix}(0.146,0.385,1.090),\\(0.306,0.624,1.573)\end{bmatrix} & \begin{bmatrix}(0.292,0.553,1.364),\\(0.439,0.775,1.811)\end{bmatrix} & \begin{bmatrix}(0.268,0.547,1.403),\\(0.388,0.745,1.831)\end{bmatrix} & \begin{bmatrix}(0.016,0.164,0.737),\\(0.106,0.358,1.176)\end{bmatrix}
\end{bmatrix}$$

Rough-fuzzy total direction relation matrix of VR51-VR54 within the group VR5:

$$RN\left(\tilde{T}_5\right) = \begin{bmatrix} \begin{bmatrix} (0.010, 0.112, 0.406), \\ (0.043, 0.161, 0.423) \end{bmatrix} & \begin{bmatrix} (0.014, 0.129, 0.393), \\ (0.047, 0.171, 0.405) \end{bmatrix} & \begin{bmatrix} (0.013, 0.129, 0.394), \\ (0.040, 0.161, 0.390) \end{bmatrix} & \begin{bmatrix} (0.032, 0.169, 0.451), \\ (0.126, 0.261, 0.510) \end{bmatrix} \\ \begin{bmatrix} (0.282, 0.483, 0.937), \\ (0.420, 0.630, 1.044) \end{bmatrix} & \begin{bmatrix} (0.026, 0.137, 0.451), \\ (0.082, 0.223, 0.526) \end{bmatrix} & \begin{bmatrix} (0.144, 0.307, 0.665), \\ (0.259, 0.424, 0.746) \end{bmatrix} & \begin{bmatrix} (0.064, 0.246, 0.632), \\ (0.174, 0.375, 0.739) \end{bmatrix} \\ \begin{bmatrix} (0.395, 0.635, 1.185), \\ (0.468, 0.703, 1.169) \end{bmatrix} & \begin{bmatrix} (0.159, 0.356, 0.793), \\ (0.255, 0.450, 0.824) \end{bmatrix} & \begin{bmatrix} (0.076, 0.224, 0.619), \\ (0.121, 0.275, 0.609) \end{bmatrix} & \begin{bmatrix} (0.339, 0.535, 0.987), \\ (0.401, 0.601, 0.996) \end{bmatrix} \\ \begin{bmatrix} (0.215, 0.439, 0.934), \\ (0.318, 0.536, 0.960) \end{bmatrix} & \begin{bmatrix} (0.223, 0.388, 0.764), \\ (0.314, 0.479, 0.809) \end{bmatrix} & \begin{bmatrix} (0.196, 0.363, 0.742), \\ (0.244, 0.408, 0.733) \end{bmatrix} & \begin{bmatrix} (0.068, 0.205, 0.571), \\ (0.123, 0.277, 0.608) \end{bmatrix} \end{bmatrix}$$

Rough-fuzzy total direction relation matrix of groups of VR1-VR5:

$$RN\left(\tilde{T}_g\right) = \begin{bmatrix} \begin{bmatrix} (0.030,0.094,0.255), \\ (0.068,0.164,0.364) \end{bmatrix} & \begin{bmatrix} (0.066,0.159,0.336), \\ (0.131,0.247,0.457) \end{bmatrix} & \begin{bmatrix} (0.157,0.293,0.544), \\ (0.275,0.426,0.705) \end{bmatrix} & \begin{bmatrix} (0.075,0.160,0.336), \\ (0.121,0.226,0.437) \end{bmatrix} & \begin{bmatrix} (0.197,0.306,0.527), \\ (0.249,0.400,0.661) \end{bmatrix} \\ \begin{bmatrix} (0.142,0.257,0.486), \\ (0.224,0.360,0.616) \end{bmatrix} & \begin{bmatrix} (0.039,0.116,0.297), \\ (0.080,0.185,0.401) \end{bmatrix} & \begin{bmatrix} (0.303,0.447,0.739), \\ (0.359,0.526,0.842) \end{bmatrix} & \begin{bmatrix} (0.166,0.259,0.468), \\ (0.191,0.306,0.546) \end{bmatrix} & \begin{bmatrix} (0.228,0.360,0.628), \\ (0.326,0.484,0.783) \end{bmatrix} \\ \begin{bmatrix} (0.015,0.082,0.226), \\ (0.057,0.149,0.328) \end{bmatrix} & \begin{bmatrix} (0.011,0.073,0.206), \\ (0.046,0.136,0.303) \end{bmatrix} & \begin{bmatrix} (0.017,0.067,0.225), \\ (0.051,0.135,0.334) \end{bmatrix} & \begin{bmatrix} (0.017,0.048,0.188), \\ (0.067,0.131,0.309) \end{bmatrix} & \begin{bmatrix} (0.065,0.142,0.309), \\ (0.113,0.217,0.427) \end{bmatrix} \\ \begin{bmatrix} (0.183,0.300,0.565), \\ (0.276,0.419,0.687) \end{bmatrix} & \begin{bmatrix} (0.174,0.285,0.513), \\ (0.221,0.358,0.610) \end{bmatrix} & \begin{bmatrix} (0.350,0.500,0.824), \\ (0.412,0.589,0.913) \end{bmatrix} & \begin{bmatrix} (0.054,0.124,0.329), \\ (0.095,0.195,0.427) \end{bmatrix} & \begin{bmatrix} (0.229,0.368,0.680), \\ (0.339,0.510,0.825) \end{bmatrix} \\ \begin{bmatrix} (0.080,0.174,0.359), \\ (0.135,0.246,0.454) \end{bmatrix} & \begin{bmatrix} (0.043,0.143,0.316), \\ (0.124,0.233,0.427) \end{bmatrix} & \begin{bmatrix} (0.180,0.302,0.540), \\ (0.227,0.366,0.624) \end{bmatrix} & \begin{bmatrix} (0.099,0.179,0.348), \\ (0.139,0.233,0.427) \end{bmatrix} & \begin{bmatrix} (0.044,0.124,0.314), \\ (0.093,0.200,0.421) \end{bmatrix} \end{bmatrix}$$

The next step is to defuzzyfy the fuzzy value from the rough-fuzzy total direct-relation matrices by applying the Eq. (30)~(31), thus forming the rough dependence matrices within each group (Step 3.5). The rough dependence matrix of the group VR1 is shown as follows:

$$RN(T) = \begin{bmatrix} [0.079, 0.202] & [0.333, 0.496] & [0.362, 0.563] & [0.079, 0.243] \\ [0.165, 0.331] & [0.170, 0.257] & [0.541, 0.587] & [0.095, 0.229] \\ [0.127, 0.230] & [0.258, 0.315] & [0.153, 0.230] & [0.067, 0.209] \\ [0.251, 0.374] & [0.469, 0.540] & [0.488, 0.575] & [0.062, 0.169] \end{bmatrix}$$

In order to form the initial supermatrix in the last step of this model, the normalized crisp dependence matrix is required (Step 3.6). Thus, the crisp dependence matrix is obtained by using the Eq. (32), taking the value of optimistic indicator λ as 0.5. Then by dividing the element of each column by the sum of the related column, the normalized dependence matrix is formed. Table 2 shows the normalized dependence matrix of VRs within each group. Table 3 shows the normalized dependence matrix of the five VR groups. All of these dependences will be inputs for creating the initial supermatrix in Step 5.

Relations between value requirements belonging to different VR groups are established by applying the rough-fuzzy ANP method (Step 4). The process of determining the dependencies is illustrated on the example of determining the dependencies of the VR1 group in relation to the value requirement VR21: Remote monitoring. Fuzzy scores are obtained by converting the linguistic evaluations of decision-makers using the relations given in Table 1. Other evaluations are conducted in the same manner. The upper triangular form of group fuzzy pair-wise judgement matrix of the VR1 group with respect to VR21 is shown as follows:

$$\tilde{A}=\begin{bmatrix} \begin{pmatrix}\{1,1,1,1,1\},\\ \{1,1,1,1,1\},\\ \{1,1,1,1,1\}\end{pmatrix} & \begin{pmatrix}\{3,3,1,1,6\},\\ \{4,4,2,2,7\},\\ \{5,5,3,3,8\}\end{pmatrix} & \begin{pmatrix}\{5,6,3,3,1\},\\ \{6,7,4,4,2\},\\ \{7,8,5,5,3\}\end{pmatrix} & \begin{pmatrix}\{8,6,8,9,6\},\\ \{9,7,9,10,7\},\\ \{10,8,10,10,8\}\end{pmatrix} \\ & \begin{pmatrix}\{1,1,1,1,1\},\\ \{1,1,1,1,1\},\\ \{1,1,1,1,1\}\end{pmatrix} & \begin{pmatrix}\{6,5,1,2,6\},\\ \{7,6,2,3,7\},\\ \{8,7,3,4,8\}\end{pmatrix} & \begin{pmatrix}\{8,6,6,8,8\},\\ \{9,7,7,9,9\},\\ \{10,8,8,10,10\}\end{pmatrix} \\ & & \begin{pmatrix}\{1,1,1,1,1\},\\ \{1,1,1,1,1\},\\ \{1,1,1,1,1\}\end{pmatrix} & \begin{pmatrix}\{5,2,5,5,5\},\\ \{6,3,6,6,6\},\\ \{7,4,7,7,7\}\end{pmatrix} \\ & & & \begin{pmatrix}\{1,1,1,1,1\},\\ \{1,1,1,1,1\},\\ \{1,1,1,1,1\}\end{pmatrix} \end{bmatrix}$$

By applying Eq. (16)~(23), each fuzzy element of the group evaluation matrix is converted to rough-fuzzy number form. The rough-fuzzy judgement matrix is obtained as follows (Step 4.2):

$$RN\left(\tilde{A}\right)=\begin{bmatrix} \begin{bmatrix}(1.000,1.000,1.000),\\(1.000,1.000,1.000)\end{bmatrix} & \begin{bmatrix}(1.461,2.553,3.600),\\(3.351,4.512,5.596)\end{bmatrix} & \begin{bmatrix}(2.028,3.164,4.230),\\(4.403,5.486,6.531)\end{bmatrix} & \begin{bmatrix}(6.610,7.618,8.670),\\(8.021,9.030,9.649)\end{bmatrix} \\ & \begin{bmatrix}(1.000,1.000,1.000),\\(1.000,1.000,1.000)\end{bmatrix} & \begin{bmatrix}(2.001,3.173,4.266),\\(4.917,6.022,7.077)\end{bmatrix} & \begin{bmatrix}(6.655,7.663,8.670),\\(7.640,8.645,9.649)\end{bmatrix} \\ & & \begin{bmatrix}(1.000,1.000,1.000),\\(1.000,1.000,1.000)\end{bmatrix} & \begin{bmatrix}(3.595,4.675,5.723),\\(4.820,5.836,6.845)\end{bmatrix} \\ & & & \begin{bmatrix}(1.000,1.000,1.000),\\(1.000,1.000,1.000)\end{bmatrix} \end{bmatrix}$$

To respectively obtain lower and upper boundary of rough priority vector of $RN(\tilde{A})$ (Step 4.3), the rough-fuzzy matrix is separated into two matrices: lower limit fuzzy matrix $\tilde{A}^L$ and upper limit fuzzy matrix $\tilde{A}^U$ as follows:

$$\tilde{A}^L=\begin{bmatrix} (1.000,1.000,1.000) & (1.461,2.553,3.600) & (2.028,3.164,4.230) & (6.610,7.618,8.670) \\ & (1.000,1.000,1.000) & (2.001,3.173,4.266) & (6.655,7.663,8.670) \\ & & (1.000,1.000,1.000) & (3.595,4.675,5.723) \\ & & & (1.000,1.000,1.000) \end{bmatrix}$$

$$\tilde{A}^U=\begin{bmatrix} (1.000,1.000,1.000) & (3.351,4.512,5.596) & (4.403,5.486,6.531) & (8.021,9.030,9.649) \\ & (1.000,1.000,1.000) & (4.917,6.022,7.077) & (7.640,8.645,9.649) \\ & & (1.000,1.000,1.000) & (4.820,5.836,6.845) \\ & & & (1.000,1.000,1.000) \end{bmatrix}$$

Then the priority vector of the fuzzy matrix is obtained by using the LFPP model (40) and Eq. (41). Taking the determining process of priority vector for $\tilde{A}^L$ as an example shown as follows:

First, since $\tilde{A}^L$ is a 4×4 fuzzy matrix, the LFPP model (40) can be expanded as follows:

$$\begin{aligned}
&\text{Minimize} \quad J\\
&J=\left(1-\lambda^L\right)^2+10000\times\sum_{i=1}^{3}\sum_{j=i+1}^{4}\left(\left(\delta_{ij}^L\right)^2+\left(\eta_{ij}^L\right)^2\right)\\
&s.j.\begin{cases}
x_1^L-x_2^L-\lambda^L\ln\left(m_{12}^{aL}/l_{12}^{aL}\right)+\delta_{12}^L\ge\ln\left(l_{12}^{aL}\right),\\
-x_1^L+x_2^L-\lambda^L\ln\left(u_{12}^{aL}/m_{12}^{aL}\right)+\eta_{12}^L\ge\ln\left(u_{12}^{aL}\right),\\
x_1^L-x_3^L-\lambda^L\ln\left(m_{13}^{aL}/l_{13}^{aL}\right)+\delta_{13}^L\ge\ln\left(l_{13}^{aL}\right),\\
-x_1^L+x_3^L-\lambda^L\ln\left(u_{13}^{aL}/m_{13}^{aL}\right)+\eta_{13}^L\ge\ln\left(u_{13}^{aL}\right),\\
x_1^L-x_4^L-\lambda^L\ln\left(m_{14}^{aL}/l_{14}^{aL}\right)+\delta_{14}^L\ge\ln\left(l_{14}^{aL}\right),\\
-x_1^L+x_4^L-\lambda^L\ln\left(u_{14}^{aL}/m_{14}^{aL}\right)+\eta_{14}^L\ge\ln\left(u_{14}^{aL}\right),\\
x_2^L-x_3^L-\lambda^L\ln\left(m_{23}^{aL}/l_{23}^{aL}\right)+\delta_{23}^L\ge\ln\left(l_{23}^{aL}\right),\\
-x_2^L+x_3^L-\lambda^L\ln\left(u_{23}^{aL}/m_{23}^{aL}\right)+\eta_{23}^L\ge\ln\left(u_{23}^{aL}\right),\\
x_2^L-x_4^L-\lambda^L\ln\left(m_{24}^{aL}/l_{24}^{aL}\right)+\delta_{24}^L\ge\ln\left(l_{24}^{aL}\right),\\
-x_2^L+x_4^L-\lambda^L\ln\left(u_{24}^{aL}/m_{24}^{aL}\right)+\eta_{24}^L\ge\ln\left(u_{24}^{aL}\right),\\
x_3^L-x_4^L-\lambda^L\ln\left(m_{34}^{aL}/l_{34}^{aL}\right)+\delta_{34}^L\ge\ln\left(l_{34}^{aL}\right),\\
-x_3^L+x_4^L-\lambda^L\ln\left(u_{34}^{aL}/m_{34}^{aL}\right)+\eta_{34}^L\ge\ln\left(u_{34}^{aL}\right),\\
\lambda^L,x_1,x_2,x_3,x_4,\delta_{12}^L,\delta_{13}^L,\delta_{14}^L,\delta_{23}^L,\delta_{24}^L,\delta_{34}^L,\eta_{12}^L,\eta_{13}^L,\eta_{14}^L,\eta_{23}^L,\eta_{24}^L,\eta_{34}^L\ge 0.
\end{cases}
\end{aligned} \tag{45}$$

Then, the known parameters required in the expanded model are extracted from $\tilde{A}^L$, as shown in Table 4.

By combining the parameters in Table 4, the expanded model (45) can be written as follows:

$$\begin{aligned}
&\text{Minimize} \quad J\\
&J=\left(1-\lambda^L\right)^2+10000\times\sum_{i=1}^{3}\sum_{j=i+1}^{4}\left(\left(\delta_{ij}^L\right)^2+\left(\eta_{ij}^L\right)^2\right)\\
&s.j.\begin{cases}
x_1^L-x_2^L-\lambda^L\ln(2.553/1.461)+\delta_{12}^L\ge\ln(1.461),\\
-x_1^L+x_2^L-\lambda^L\ln(3.600/2.553)+\eta_{12}^L\ge\ln(3.600),\\
x_1^L-x_3^L-\lambda^L\ln(3.164/2.028)+\delta_{13}^L\ge\ln(2.028),\\
-x_1^L+x_3^L-\lambda^L\ln(4.230/3.164)+\eta_{13}^L\ge\ln(4.230),\\
x_1^L-x_4^L-\lambda^L\ln(7.618/6.610)+\delta_{14}^L\ge\ln(6.610),\\
-x_1^L+x_4^L-\lambda^L\ln(8.670/7.618)+\eta_{14}^L\ge\ln(8.670),\\
x_2^L-x_3^L-\lambda^L\ln(3.173/2.001)+\delta_{23}^L\ge\ln(2.001),\\
-x_2^L+x_3^L-\lambda^L\ln(4.266/3.173)+\eta_{23}^L\ge\ln(4.266),\\
x_2^L-x_4^L-\lambda^L\ln(7.663/6.655)+\delta_{24}^L\ge\ln(6.655),\\
-x_2^L+x_4^L-\lambda^L\ln(8.670/7.663)+\eta_{24}^L\ge\ln(8.670),\\
x_3^L-x_4^L-\lambda^L\ln(4.675/3.595)+\delta_{34}^L\ge\ln(3.595),\\
-x_3^L+x_4^L-\lambda^L\ln(5.723/4.675)+\eta_{34}^L\ge\ln(5.723),\\
\lambda^L,x_1,x_2,x_3,x_4,\delta_{12}^L,\delta_{13}^L,\delta_{14}^L,\delta_{23}^L,\delta_{24}^L,\delta_{34}^L,\eta_{12}^L,\eta_{13}^L,\eta_{14}^L,\eta_{23}^L,\eta_{24}^L,\eta_{34}^L\ge 0.
\end{cases}
\end{aligned}$$

This model is calculated to find the optimal solution by using the computing software MATLAB R2014a. By normalizing the optimal solution obtained from this model using Eq. (41), the lower limit priority vector is determined as 0.453, 0.327, 0.171 and 0.050. With the same procedure, the upper limit priority vector is acquired as 0.575, 0.290, 0.100 and 0.035. By applying Eq. (42), the normalized crisp priority vector is obtained (0.514, 0.309, 0.135 and 0.042) with giving value of β as 0.5 (Step 4.4). The normalized crisp priority vector of other rough-fuzzy judgement matrices can also be obtained in the same manner. All of these obtained weight vectors, in addition to the values of the dependence matrices of value requirements within the same group, are used as inputs for the formation of the supermatrix in the next step.

By entering the dependence matrices found by the rough-fuzzy DEMATEL and rough-fuzzy ANP into the corresponding positions, initial supermatrix can be constructed (Step 5.1) as shown in Table 5.

Table 2
Normalized dependence matrix of VRs within each group ($\lambda = 0.5$).

T_N^1 (VR1, $\lambda = 0.5$)	VR11	VR12	VR13	VR14
VR11	0.152	0.290	0.262	0.273
VR12	0.279	0.149	0.325	0.291
VR13	0.202	0.202	0.108	0.234
VR14	0.367	0.359	0.305	0.202
T_N^2 (VR2, $\lambda = 0.5$)	VR21	VR22	VR23	VR24
VR21	0.167	0.261	0.242	0.259
VR22	0.263	0.169	0.300	0.263
VR23	0.215	0.222	0.143	0.254
VR24	0.355	0.347	0.315	0.224
T_N^3 (VR3, $\lambda = 0.5$)	VR31	VR32	VR33	
VR31	0.263	0.405	0.361	
VR32	0.420	0.272	0.440	
VR33	0.317	0.323	0.199	
T_N^4 (VR4, $\lambda = 0.5$)	VR41	VR42	VR43	VR44
VR41	0.187	0.265	0.276	0.283
VR42	0.288	0.180	0.272	0.256
VR43	0.202	0.220	0.146	0.237
VR44	0.323	0.335	0.307	0.224
T_N^5 (VR5, $\lambda = 0.5$)	VR51	VR52	VR53	VR54
VR51	0.082	0.133	0.132	0.161
VR52	0.296	0.162	0.311	0.232
VR53	0.358	0.341	0.226	0.419
VR54	0.264	0.363	0.331	0.189

Table 3
Normalized dependence matrix of VR groups ($\lambda = 0.5$).

T_N^g (VR5, $\lambda = 0.5$)	VR1	VR2	VR3	VR4	VR5
VR1	0.119	0.208	0.195	0.204	0.225
VR2	0.272	0.161	0.265	0.300	0.269
VR3	0.105	0.110	0.061	0.101	0.117
VR4	0.317	0.331	0.296	0.176	0.281
VR5	0.187	0.191	0.183	0.218	0.108

Table 4
Parameters of LFPP model.

$i = 1, \ldots, 3$	$i = 1$			$i = 2$		$i = 3$
$j = i + 1, \ldots, 4$	$j = 2$	$j = 3$	$j = 4$	$j = 3$	$j = 4$	$j = 4$
l_{ij}^{aL}	1.461	2.028	6.610	2.001	6.655	3.595
m_{ij}^{aL}	2.553	3.164	7.618	3.173	7.663	4.675
u_{ij}^{aL}	3.600	4.230	8.669	4.266	8.669	5.723

Then, according to Step 5.2, by combining Eq. (43) and the matrix T_N^g shown in Table 4, weighted supermatrix is obtained. By normalizing weighted matrix supermatrix W_W by the sum of related column, normalized weighted supermatrix W_{NW} is informed as shown in Table 6.

By raising the normalized weighted supermatrix in Table 6 to the power $2m + 1$, where m is a sufficiently large number, the normalized weighted supermatrix is converging thus forming the limit supermatrix (Step 5.3). The limit supermatrix is computed by applying the computing software MATLAB R2014a. Finally, converged values in the columns are used as the priorities of the value requirements. The solution of the illustrated example shows that when the global optimistic indicator through the model equal 0.5, the ranking of each value requirement is as follows:

VR42 (0.1042) > VR41 (0.0826) > VR21 (0.0790) > VR22 (0.0758) > VR23 (0.0746) > VR53 (0.0724) > VR52 (0.0713) > VR12 (0.0647) > VR54 (0.0642) > VR11 (0.0619) > VR43 (0.0504) > VR44 (0.0481) > VR51 (0.0377) > VR13 (0.0371) > VR24 (0.0355) > VR14 (0.0183) > VR31 (0.0133) > VR32 (0.0069) > VR33 (0.0019)

From the above priorities, it is indicated that the top five important requirements for a sustainable excavator service system are respectively VR42 (Health management for keeping the excavator in a healthy status), VR41 (Proactive maintenance for preventing certain unscheduled stoppages of excavator), VR21 (Remote monitoring the excavator by connecting it into the monitoring platform), VR22 (Fault diagnosis by data-based analysis of the excavator status) and VR23 (Timely repair based on the fast support provided by the manufacturer). Those requirements should be given much priority when design an excavator service system for sustainability. The sum of weights of all value requirements within each requirement group is respectively VR1: 0.1820, VR2: 0.2650, VR3: 0.0221, VR4: 0.2853 and VR5: 0.2455, which reflects that those value requirements elicited from value deteriorated and value failed have bigger influences on the PSS sustainability. VR42 and VR41 are considered to be the top two important requirements because they are the basis for enabling excavator more sustainable and optimal. In this aspect, importance of VR42 and VR41 would affect the planning of service module of the sustainable PSS in the later design phase. The decision-making basis for resources allocation of different service module is provided by the importance ranking of value requirements obtained from the proposed model.

Table 5
Initial supermatrix.

W_I	VR11	VR12	VR13	VR14	VR21	VR22	VR23	VR24	VR31	VR32	VR33	VR41	VR42	VR43	VR44	VR51	VR52	VR53	VR54
VR11	**0.152**	**0.290**	**0.261**	**0.273**	0.514	0.559	0.504	0.440	0.168	0.181	0.202	0.362	0.123	0.271	0.176	0.000	0.000	0.000	0.000
VR12	**0.278**	**0.149**	**0.325**	**0.291**	0.309	0.156	0.166	0.350	0.575	0.566	0.548	0.313	0.627	0.432	0.494	0.000	0.000	0.000	0.000
VR13	**0.203**	**0.203**	**0.108**	**0.234**	0.135	0.233	0.250	0.118	0.142	0.138	0.134	0.274	0.191	0.202	0.226	0.000	0.000	0.000	0.000
VR14	**0.366**	**0.359**	**0.305**	**0.202**	0.042	0.052	0.080	0.091	0.114	0.115	0.116	0.052	0.059	0.095	0.104	0.000	0.000	0.000	0.000
VR21	0.341	0.331	0.334	0.373	**0.167**	**0.261**	**0.242**	**0.259**	0.287	0.305	0.258	0.460	0.196	0.042	0.489	0.000	0.332	0.000	0.000
VR22	0.334	0.304	0.279	0.269	**0.263**	**0.169**	**0.300**	**0.263**	0.530	0.385	0.473	0.290	0.206	0.135	0.301	0.000	0.489	0.000	0.000
VR23	0.274	0.299	0.319	0.290	**0.215**	**0.222**	**0.143**	**0.254**	0.099	0.230	0.187	0.201	0.546	0.519	0.162	0.000	0.071	0.000	0.000
VR24	0.051	0.066	0.068	0.069	**0.355**	**0.347**	**0.315**	**0.224**	0.084	0.079	0.082	0.049	0.052	0.304	0.049	0.000	0.109	0.000	0.000
VR31	0.720	0.577	0.571	0.625	0.000	0.000	0.000	0.000	**0.263**	**0.405**	**0.361**	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
VR32	0.219	0.353	0.355	0.310	0.000	0.000	0.000	0.000	**0.420**	**0.272**	**0.440**	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
VR33	0.062	0.071	0.074	0.066	0.000	0.000	0.000	0.000	**0.317**	**0.323**	**0.199**	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
VR41	0.527	0.054	0.049	0.359	0.248	0.170	0.555	0.477	0.250	0.259	0.275	**0.187**	**0.265**	**0.276**	**0.283**	0.000	0.371	0.000	0.000
VR42	0.249	0.501	0.171	0.265	0.568	0.653	0.307	0.350	0.539	0.459	0.477	**0.288**	**0.180**	**0.272**	**0.256**	0.000	0.193	0.000	0.000
VR43	0.176	0.258	0.278	0.309	0.068	0.070	0.068	0.099	0.129	0.124	0.169	**0.202**	**0.220**	**0.146**	**0.237**	0.000	0.379	0.000	0.000
VR44	0.048	0.188	0.501	0.067	0.117	0.107	0.070	0.074	0.082	0.158	0.079	**0.323**	**0.335**	**0.307**	**0.224**	0.000	0.057	0.000	0.000
VR51	0.198	0.425	0.000	0.000	0.000	0.000	0.157	0.144	0.000	0.000	0.000	0.000	0.000	0.174	0.000	**0.082**	**0.133**	**0.132**	**0.161**
VR52	0.494	0.386	0.000	0.000	0.000	0.000	0.114	0.167	0.000	0.000	0.000	0.000	0.000	0.595	0.000	**0.296**	**0.162**	**0.311**	**0.232**
VR53	0.251	0.081	0.000	0.000	0.000	0.000	0.224	0.324	0.000	0.000	0.000	0.000	0.000	0.142	0.000	**0.358**	**0.341**	**0.226**	**0.419**
VR54	0.057	0.107	0.000	0.000	0.000	0.000	0.506	0.365	0.000	0.000	0.000	0.000	0.000	0.090	0.000	**0.264**	**0.363**	**0.331**	**0.189**

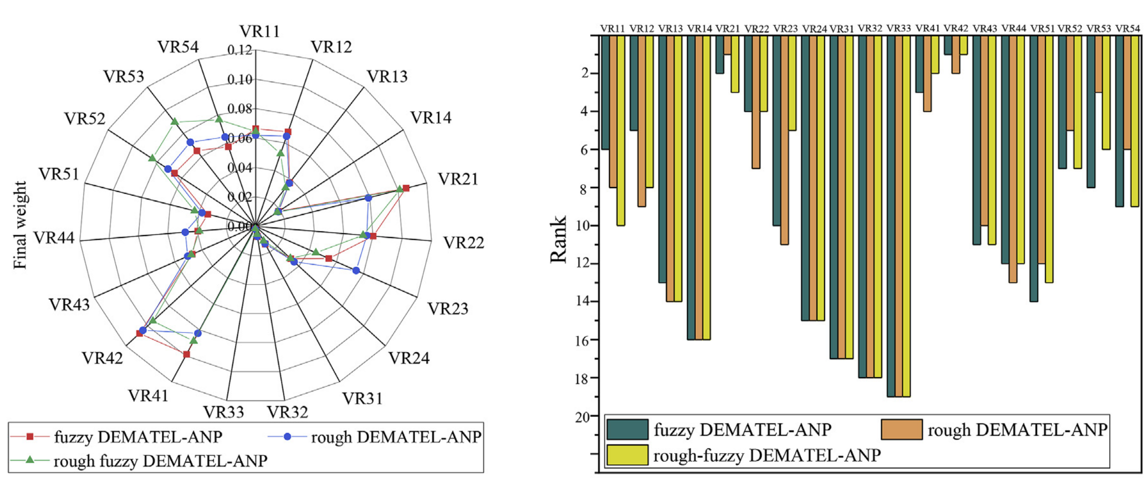
Table 6
Normalized weighted supermatrix.

W_{NW}	VR11	VR12	VR13	VR14	VR21	VR22	VR23	VR24	VR31	VR32	VR33	VR41	VR42	VR43	VR44	VR51	VR52	VR53	VR54
VR11	0.018	0.034	0.038	0.040	0.153	0.166	0.118	0.103	0.040	0.043	0.048	0.109	0.037	0.061	0.053	0.000	0.000	0.000	0.000
VR12	0.033	0.018	0.048	0.042	0.092	0.046	0.039	0.082	0.137	0.135	0.131	0.094	0.188	0.098	0.148	0.000	0.000	0.000	0.000
VR13	0.024	0.024	0.016	0.034	0.040	0.069	0.058	0.028	0.034	0.033	0.032	0.082	0.057	0.046	0.068	0.000	0.000	0.000	0.000
VR14	0.044	0.043	0.045	0.030	0.013	0.015	0.019	0.021	0.027	0.027	0.028	0.016	0.018	0.022	0.031	0.000	0.000	0.000	0.000
VR21	0.093	0.090	0.112	0.125	0.038	0.060	0.044	0.047	0.093	0.099	0.084	0.203	0.087	0.014	0.216	0.000	0.136	0.000	0.000
VR22	0.091	0.083	0.093	0.090	0.060	0.039	0.054	0.047	0.172	0.125	0.153	0.128	0.091	0.045	0.132	0.000	0.200	0.000	0.000
VR23	0.074	0.081	0.107	0.097	0.049	0.051	0.026	0.046	0.032	0.075	0.061	0.089	0.241	0.173	0.071	0.000	0.029	0.000	0.000
VR24	0.014	0.018	0.023	0.023	0.082	0.080	0.057	0.040	0.027	0.026	0.027	0.022	0.023	0.101	0.021	0.000	0.044	0.000	0.000
VR31	0.076	0.061	0.074	0.081	0.000	0.000	0.000	0.000	0.020	0.030	0.027	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
VR32	0.023	0.037	0.046	0.040	0.000	0.000	0.000	0.000	0.031	0.020	0.033	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
VR33	0.006	0.007	0.010	0.009	0.000	0.000	0.000	0.000	0.024	0.024	0.015	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
VR41	0.167	0.017	0.019	0.140	0.117	0.081	0.206	0.177	0.091	0.094	0.100	0.049	0.069	0.054	0.073	0.000	0.158	0.000	0.000
VR42	0.079	0.159	0.067	0.103	0.269	0.309	0.114	0.130	0.196	0.167	0.173	0.075	0.047	0.053	0.066	0.000	0.082	0.000	0.000
VR43	0.056	0.082	0.109	0.120	0.032	0.033	0.025	0.037	0.047	0.045	0.061	0.052	0.057	0.029	0.062	0.000	0.162	0.000	0.000
VR44	0.015	0.060	0.196	0.026	0.055	0.051	0.026	0.027	0.030	0.057	0.029	0.084	0.087	0.060	0.058	0.000	0.024	0.000	0.000
VR51	0.037	0.080	0.000	0.000	0.000	0.000	0.034	0.031	0.000	0.000	0.000	0.000	0.000	0.042	0.000	0.082	0.022	0.132	0.161
VR52	0.092	0.072	0.000	0.000	0.000	0.000	0.024	0.036	0.000	0.000	0.000	0.000	0.000	0.144	0.000	0.296	0.027	0.311	0.232
VR53	0.047	0.015	0.000	0.000	0.000	0.000	0.048	0.069	0.000	0.000	0.000	0.000	0.000	0.034	0.000	0.358	0.056	0.226	0.419
VR54	0.011	0.020	0.000	0.000	0.000	0.000	0.108	0.078	0.000	0.000	0.000	0.000	0.000	0.022	0.000	0.264	0.060	0.331	0.189

4.4. Comparison and discussion

The effectiveness and strength of the proposed model are demonstrated by comparing rough-fuzzy DEMATEL-ANP evaluation model for sustainable PSS value requirement with some related methods or models. In order to evaluate the efficiency and accuracy of the rough-fuzzy DEMATEL-ANP hybrid model, the comparisons of the priorities of value requirements with using fuzzy DEMATEL-ANP (Tadić et al., 2014) and rough DEMATEL-ANP model are conducted. In fuzzy DEMATEL-ANP method, the geometric means of multiple fuzzy judgements are taking as the group average fuzzy intervals number. For rough DEMATEL-ANP method, the group average rough intervals number is informed by aggregating multiple crisp judgements using rough set approach. The body procedure of DEMATEL-ANP for the three models are basically identical. As shown in Fig. 6., the priority of each value requirement is presented by adopting the three methods. It is indicated that the value requirements' weights from the fuzzy-, rough-, and rough-fuzzy- DEMATEL-ANP are almost different with each other. For example, the rough-fuzzy approach considers the VR42: Health management for keeping the excavator in a healthy status, as the most important requirement for sustainable excavator PSS. However, in the fuzzy approach, the VR41: Proactive maintenance for preventing certain unscheduled stoppages of excavator, is considered as the most important value requirement. The other value requirements also have distinct ranks, such as VR12, VR22, VR53, VR52, etc. The weights difference among the three methods are derived from the different manipulation mechanism of individual vagueness and group subjectivity.

To compare the difference of fuzzy set, rough set and rough-fuzzy set method, the judgement scores of VR11 relative to VR12 in the comparison process of VR1 group are taking an example. The five selected DMs rate the importance degree of VR11 relative to VR12 as 4, 4, 7, 6, and 3. For the group judgements, the corresponding fuzzy interval are [3, 5], [3, 5], [6, 8], [5, 7], and [2, 4]; the rough interval are [3.634, 5.092], [3.634, 5.092], [4.580, 7.000], [4.120, 6.481], [3.520, 5.619] and [3.000, 4.580]; and the rough-fuzzy interval with $\lambda = 0.5$ are [3.337, 5.379], [3.337, 5.379], [4.760, 6.809], [4.279, 6.314] and [2.760, 4.809]. As shown in Fig. 7, the fuzzy interval mainly reflects the vagueness in thinking and expressing preferences of individual DM. It does not truly indicates the actual situation of the judgements, because the boundary



(a) Weights of value requirements

(b) Rank of value requirements

Fig. 6. Comparisons of evaluation results among fuzzy, rough and the proposed rough-fuzzy DEMATEL-ANP in terms of (a) Weights of value requirements and (b) Rank of value requirements.

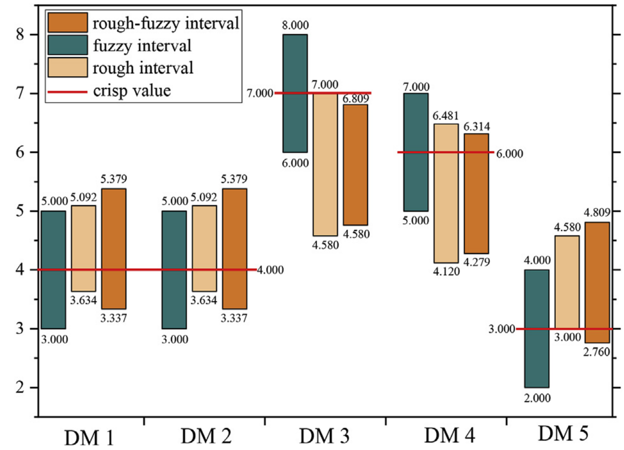


Fig. 7. Comparisons among the fuzzy, rough and the proposed rough-fuzzy interval of crisp group judgements.

interval that denotes estimation range in value requirement evaluation process varies across DMs who have different knowledge, experience and expertise. Normally, the rough interval performs well to reflect the actual heterogeneity of DMs group, while not considering fuzziness of individual DM's linguistic expression. In the two aspects, the rough-fuzzy interval combines the advantages of fuzzy method and rough method for dealing with the vagueness and heterogeneity characters of the group decisions. For example, DM5 gives the lowest score 3 in the group judgements. The low boundary of the fuzzy interval [2, 4] is over estimated comparing with the rough-fuzzy method, since it neglects the influences of other DMs who give higher rate. Under the same reasons, the up boundary of the fuzzy interval is lower than the rough-fuzzy interval. While the lower boundary of the rough interval [3.000, 4.580] is higher than the rough-fuzzy interval [2.760, 4.809], due to its ignorance of the vagueness of DM5's decision. Apparently, the up boundary of the rough interval is lower than the rough-fuzzy interval. The group average interval from the rough-fuzzy method is [3.625, 5.694] which not only reflects the size of weight but also the actual estimation range. Therefore, the rough-fuzzy method provides a more accurate approach to describing the status of value requirement of PSS. The same results can be also found in other value requirements evaluation process.

Furthermore, the evaluations of dependences of value requirements in the VR1 group with using fuzzy DEMATEL (Tadić et al., 2014) and rough DEMATEL (Song and Cao, 2017) have also been conducted for comparison with the proposed rough-fuzzy DEMATEL method. The comparison results are shown in Fig. 8. The values of all elements of the dependence matrix of VR1 group calculated from the three methods are different with each other. For example, the values of the element t_{14} which denotes the degree to the influence of VR11 on VR14 are respectively 0.273 in rough-fuzzy approach, 0.421 in fuzzy approach and 0.260 in rough approach. The other elements also have different values obtained from these methods. Moreover, it is indicated that the rough-fuzzy DEMATEL combines the strengths of fuzzy DEMATEL and rough DEMATEL.

In the ANP procedure, pair-wise comparison method is regarded as a significantly key step. This method is effective to determine the related weights of the elements with respect to one object. Fuzzy set, rough set and pair-wise comparison method are combined into the proposed model. In order to reveal the differences among fuzzy, rough and rough-fuzzy pair-wise comparison method, the related weights of value requirements in VR1 group with respect to the

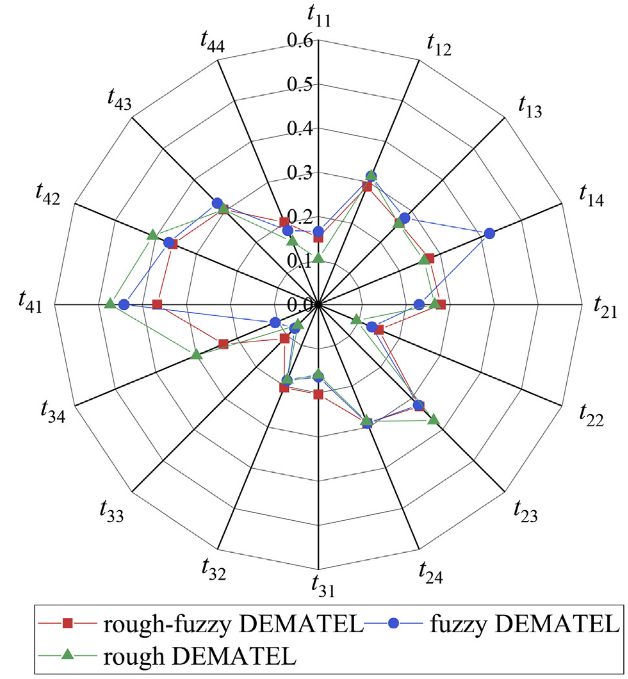


Fig. 8. Comparisons among fuzzy, rough and the proposed rough-fuzzy DEMATEL.

value requirements in VR4 group are calculated through the three methods. In the fuzzy and rough-fuzzy methods, the same non-linear programing model LFPP is used to find the optimal priorities from the comparison matrices. In the rough methods, the row vector average approach, introduced by Saaty, is used to obtain the related weights and normalize the results. As shown in Fig. 9, the weights obtained from the three methods are different with each other. For instance, the related weights of VR11, VR12, VR13 and VR14 with respect to VR41, are respectively represented by w_{11}, w_{21}, w_{31} and w_{41}. In fuzzy approach, $w_{11}=0.360$, $w_{21}=0.111$, $w_{31}=0.277$, $w_{41}=0.194$; in rough approach, $w_{11}=0.4223$, $w_{21}=0.362$, $w_{31}=0.327$, $w_{41}=0.280$; while in rough-fuzzy approach, $w_{11}=0.4223$, $w_{21}=0.362$, $w_{31}=0.327$, $w_{41}=0.280$. The results show that the LFPP model is not only effective to calculate the crisp priority vector of fuzzy triangular pair-wise matrix, but

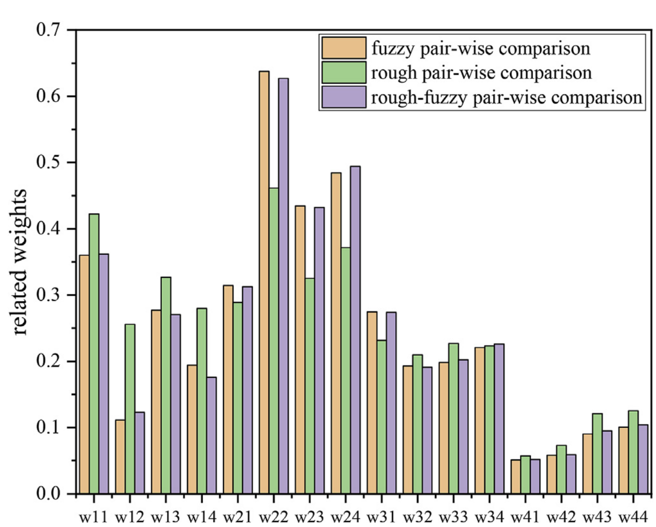


Fig. 9. Differences among fuzzy, rough and rough-fuzzy pair-wise comparison.

also adaptive to solve the same problem of rough-fuzzy pair-wise matrix.

Additionally, the proposed rough-fuzzy DEMATEL-ANP method allows the decision-making process taking different risk-bearing attitude, i.e. adopting different optimistic indicator λ in each evaluation process. The crisp weight of sustainable PSS requirement would be different with the variance of optimistic indicator. As shown in Fig. 10, the priorities distribution of value requirements under $\lambda = 0$, 0.5, 1 are slightly distinctive. For example, VR41 is ranked at the 5th, 2nd and 2nd respectively when $\lambda = 0$, 0.5, 1 (shown in Fig. 10(b)). This difference indicates that the design priority of value requirement might be changeable over the decision-maker attitude.

5. Theoretical and practical implications

5.1. Theoretical implications

From the theoretical perspective, this study contributes to develop a systematic elicitation and evaluation methodology for sustainable value requirement of PSS.

In the aspect of requirement elicitation of sustainable PSS, the proposed elicitation method embeds the sustainability concerns into the identification of PSS requirements by introducing the concept of value uncaptured into the PVSM model. This method is significantly different with the conventional methods which only focus on the customer satisfaction or the stakeholders' benefits. By applying the proposed new method, the value requirements that have high potential to help PSS deliver more sustainability (e.g. improve product efficiency, reduce product downtime, increase utilization rate, prolong use life, etc.) can be recognized and organized into a hierarchical structure. Many designers pay less attention to the sustainability concerns in the design of PSS concept. The proposed method performs well to provide them identify new value opportunities in the generation of product service concept.

In the aspect of requirements evaluation of sustainable PSS, the developed evaluation method contributes to decision theory by proposing a novel rough-fuzzy DEMATEL-ANP model. To better reveal the theoretical implications of the proposed evaluation method, the comparison between the proposed method and rough DEMATEL-ANP is conducted as follows:

(1) **Perception of the DMs' judgements:** Rough DEMATEL-ANP is able to handle the individual subjectivity and group diversity by adopting the rough set theory. The group judgements from multiple DMs are aggregated into a rough number, while missing the linguistic vagueness of individual DM's expression about the preference of different objects. However, rough-fuzzy DEMATEL-ANP gives consideration of the linguistic vagueness, individual subjectivity and group diversity. It transfers multiple fuzzy judgements into group triangular fuzzy numbers by using fuzzy membership function. Then the group fuzzy number is transited into rough-fuzzy number by using rough aggregating approaches. The method combines fuzzy set and rough set together to respectively handle the linguistic judgement vagueness and individual subjectivity as well as the group decision diversity.

(2) **Integration of the hybrid methods:** The process of integrating the rough-fuzzy method into the DEMATEL-ANP is more complicated than integrating the single fuzzy set or rough set into the DEMATEL-ANP. Although the rough-fuzzy approach-based method may not readily fall into the easily understand category, it is more actual and adaptive in the solution for most mathematically complex practical evaluation problems. The new technique LFPP is well adaptive for integrating fuzzy set and rough set in the DEMATEL-ANP model. The combination presents a good solution for fuzzification and forming the unique fuzzy grades in case of involving multiple DMs in the decision-making process. In addition, the integration of the above four methods also provides the researchers more references for comprehensively constructing an analysis model of practical problem and simultaneously handling the complex features of group decision: the judgement vagueness, group decision diversity, complex interrelationship, and heavy calculation workload.

(3) **Aggregation of DMs' judgements:** In rough-fuzzy DEMATEL-ANP, the average interval of rough-fuzzy number is obtained by integrating multiple fuzzy judgements from different experts with considering the vague preferences, and different knowledge, experience, expertise. Compared to the average rough interval, the average rough-fuzzy interval perform better to reflect the actual situation of the ambiguous and subjective judgements, since the boundary interval integrates the estimation range both presented in priori fuzzy membership function and rough aggregation.

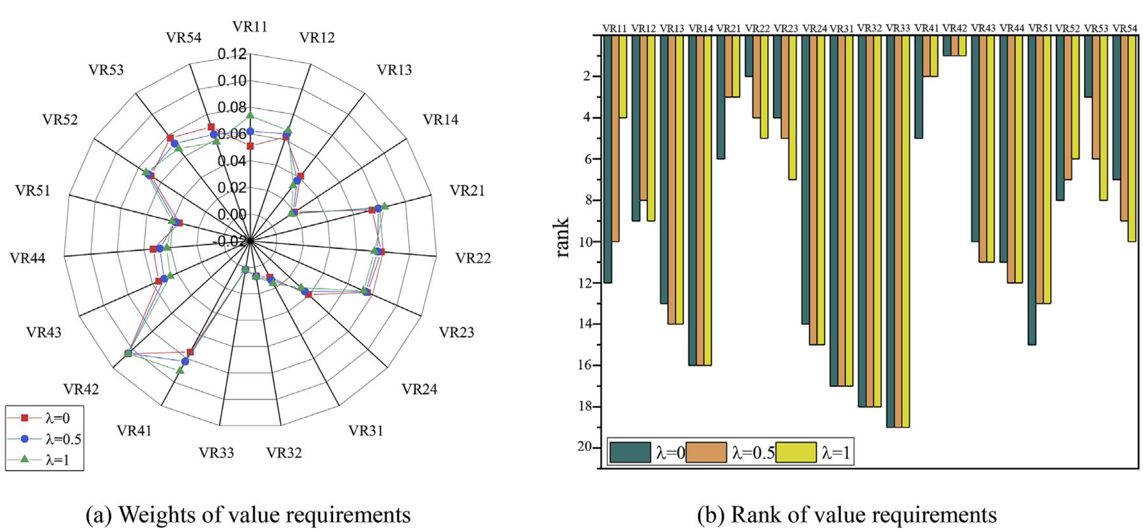


Fig. 10. Priorities of value requirements under $\lambda = 0$, 0.5, 1 in terms of (a) Weights of value requirements and (b) Rank of value requirements.

(4) **Accuracy and objectivity of the evaluation results:** In the respects of perception of the DMs' judgements, integration of hybrid methods, and aggregation of DMs' judgements, rough-fuzzy DEMATEL-ANP presents comprehensive strengths compared with alone fuzzy or rough approach. The proposed method provides more realistic and accurate results for the PSS value requirement evaluation. Since it makes a rational and effective combination of the fuzzy logic and rough logic with the DEMATEL and ANP method. Moreover, the proposed method allows the decision-making process taking different risk-bearing attitude, i.e. the DM team can adjust their evaluation strategy in accordance with the composition of team by changing the optimistic indicator.

(5) **Application prospect in the theoretical research:** The rough set has been adopted in a large number of research on the MCDM, e.g. rough AHP, rough ANP, rough DEMATEL, rough DEMATEL-ANP, rough DANP, etc., and the Multi-attributes Decision-making (MADM), e.g. rough VIKOR, rough TOPSIS, rough PROMETHEE, rough ELECTRE, rough MAIRCA, rough COPRAS, etc., for obtaining more realistic decision results in subjective environment. However, to the best of our knowledge, there are no examples in the literature of combining the rough set and fuzzy set with MCDM and MADM in the vague and heterogeneous decision environment. The integrated rough-fuzzy approach has never been occurred in any related previous research. The proposed methodology gives a novel procedure to integrate the rough-fuzzy approach into the traditional decision theory. The case study has presented obvious feasibility and validity of the rough-fuzzy approach to handling the linguistic vagueness and group diversity. The rough-fuzzy approach performs better to reflect the actual decision situation than the alone fuzzy set or rough set method. From the academic and practical perspective, it is thus believed that the proposed rough-fuzzy approach has greatly promising prospect of application in the traditional MCDM and MADM methods. There will be large amount of application scenario in future of the theoretical research, e.g. rough-fuzzy AHP, rough-fuzzy ANP, rough-fuzzy DEMATEL, rough-fuzzy DANP, rough-fuzzy VIKOR, rough-fuzzy TOPSIS, rough-fuzzy PROMETHEE, rough-fuzzy ELECTRE, rough-fuzzy MAIRCA, rough-fuzzy COPRAS, etc. Moreover, more and more properties and strength of rough-fuzzy approach can be explored through the various related research.

Besides the comparative implications, the rough-fuzzy DEMATEL-ANP also presents inherent advantages of DEMATEL-ANP. It provides feasible resolutions for manipulating complex interrelationship and heavy calculation workload of mathematically complex evaluation problems. The combination of DEMATEL and ANP integrates the strength of DEMATEL method in decomposing the complex problem into an understandable structural model and the merits of the ANP method in effectively establishing complex interrelationship among different value requirements groups. The proposed method is feasible to simplify the complex evaluation problem and reduce the calculation work in addition to provide universally applicable evaluation procedures.

5.2. Practical implications

Besides the theoretical implications, the proposed methodology provides several benefits regarding improvement of the properties of cleaner production (sustainability) in practical PSS design and management implications of requirement evaluation for sustainable PSS.

In the aspect of improving the sustainability of PSS, the proposed requirement elicitation method provides a logical, comprehensive and understandable procedure to help designers to achieve sustainable PSS concept in practice. The abstract concept of value uncaptured can be practically applied into the design method of sustainable PSS. The present method can be also used as a standardized procedure at a company to identify the value uncaptured in its offerings of product and service. Furthermore, by applying this method, the company can achieve an operable strategy of sustainable development. The proposed method helps PSS designers successfully recognize the most key value requirements with both respect of sustainability and customer satisfaction. This has potential to increase the environmental benefits and customers' loyalty.

Additionally, rough-fuzzy DEMATEL-ANP presents some benefits compared with rough DEMATEL-ANP from management perspectives, shown as follows:

- Firstly, rough-fuzzy DEMATEL-ANP makes it easy for managers to capture realistic preferences of the stakeholders whose judgements on value requirements are often imprecise, vague and ambiguous due to incomplete information or uncertainly thinking and expressing. Using the same questionnaire for acquisition of individual decision-maker's judgements, rough-fuzzy approach-based tool supports managers to obtain more accurate information compared to rough approach which does not allow converting crisp judgements into actual fuzzy form.
- Secondly, rough-fuzzy DEMATEL-ANP used in this paper is more proper to resolve actual complex evaluation problems. It is more acceptable to managers who have to deal with greater magnitudes of vagueness and imprecision in diversified and ambiguous environment and also to those who have priori knowledge of PSS requirement.
- Thirdly, in case the method is implemented as computer software or standardized procedure at a company, the time and efforts needed to get data for the method from participants to managers in practice can be marginal. The discussion based on subjectivity or biased opinions of different users of the method can be avoided, leading to efficient decision making at a company. Embedding multiple fuzzification tools into the computer software can guide inexperienced managers in decision, avoiding risk of inappropriate decision making due to lack of knowledge of priori fuzzy membership function.
- Fourthly, the proposed rough-fuzzy DEMATEL-ANP has a wider application prospect in practice. It has greater potential for solving practically complex decision problems due to its comprehensive consideration of the actual characteristics of decision issue. It can be applied widely in the requirement evaluation problems of any PSS and in other MCDM fields. Additionally, the rough-fuzzy approach can be combined into many MCDM and MADM methods to solve all kinds of practical problems. There will exist a large amount of application scenario for the proposed rough-fuzzy DEMATEL-ANP and the combined rough-fuzzy approach.

6. Conclusions

This paper develops a novel methodology to elicit and evaluate the value requirement of sustainable PSS. In the beginning of the proposed method, in order to elicit the value requirement of sustainable PSS, the PVSM model is developed based on the value uncaptured perspective and furtherly employed for identifying sustainable value opportunities in the product use life. The value requirements elicited from the PVSM model are organized into a hierarchical structure, and prioritized afterwards by the proposed rough-fuzzy DEMATEL-ANP method. The rough-fuzzy ANP method is applied for obtaining the weights of the value requirements belonged to different groups. As the complexity of the ANP problem grows exponentially with the number of elements in the structure, the problem is simplified by using the rough-fuzzy DEMATEL method for determining both the related weights of requirement groups and the strengths of value requirements among the same groups. An illustrated example of excavator PSS value requirement evaluation shows that the proposed approach is feasible and effective. The evaluation results indicate that the rough-fuzzy method provides a more accurate estimation interval to describe real human evaluation of PSS requirements. Those value requirements elicited from value deteriorated and value failed have bigger influences on the excavator PSS sustainability. The most important value requirements such like health management, proactive maintenance, remote monitoring, fault diagnosis, and timely repair are ranking at the top five value requirements and deserve more priorities in the later resources allocation and service module planning. The proposed systematic methodology presents several theoretical and practical benefits in cleaner production, requirement elicitation and evaluation compared with previous research. It should be emphasized that there is no similar research on the PSS requirement analysis using the proposed elicitation and evaluation methodologies. This study fills the gap by using an integrated framework in the specific application area. Moreover, in the surveyed literatures, no works on combining the rough set and fuzzy set theory together into the MCDM approach, have been found.

The proposed methodology can be applied for solving the evaluation problem of sustainable value requirement of any complex product service system. Also, this method can be used in other MCDM fields. Although the specific proposed method has strengths, it also has some more research to be conducted in the future. One limitation is that the proposed method does not consider the individual influence weights of DMs who have different expertise and knowledge about the issue. Thus, future research will focus on integrating the individual weights of decision makers into the evaluation process. Besides, the proposed method does not explore much about the effects of value requirements interactions on PSS development. It is necessary to research the interrelations among the value requirements and their effect on the later service module planning and resources allocation. Furthermore, more validation work is necessary to complete in other industry or fields with the object of obtaining higher validity of the method.

Acknowledgment

The author would like to thank SJTU Innovation Center of Producer Service Development, Shanghai Research Center for industrial Informatics, Shanghai Key Lab of Advanced Manufacturing Environment, National Natural Science Foundation of China (Grant No. 71632008) and Major Project for Aero engines and Gas turbines (Grant No. 2017-I-0007-0008, Grant No.2017-I-0011-0012) for the funding support to this research. In addition, the authors also appreciate the editor and anonymous reviewers for their helpful comments and suggestions on this article.

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