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A General Algorithm for Assessing Product Architecture Performance Considering Architecture Extension in Cyber Manufacturing

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Abstract

In modern manufacturing, the product architecture design options are usually restricted to those that can be produced with 100% confidence using those proven technologies to satisfy the existing customer requirement. As a result, the inefficiencies of architecture design are considerable due to such limitations. This issue is of particular interests in cyber manufacturing when exploring the tradeoff between generality and feasibility in product design and manufacturing. It can be expected that the improvement and extension of the existing product architecture may be required to meet new customer requirement when new technologies become available. An effective system performance assessment algorithm is necessary to facilitate the extension of existing product architecture. Though there has been a lot of research on architecture assessment, there is no well-defined model for level by level architecture assessment considering architecture extension. In this paper, we propose a general architecture assessment model considering the integration of additional functionality requirements and performance metrics to evaluate the architecture performance along its value pathway to meet stakeholder's requirements. A numerical case study focusing on a hypothetical auto cooling system is used to validate the effectiveness of the proposed model.

Peer-review under responsibility of the scientific committee of the Complex Adaptive Systems Conference with Theme: Engineering Cyber Physical Systems.

Keywords: Extended architecture; Architecture assessment; Renewable Sources; Automobile cooling system; multiple fuzzy model.

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1. Introduction

Defining a complete architecture and establishing an appropriate relationship network among all functional parameters of a certain product play a critical role in resolving system fuzziness for building a successful product architecture. The architecture building aiming at value creation usually begins from the need or functional requirements of the stakeholders. Since value is benefit at cost [1], it is important to balance the system complexity and performance capabilities of the product architecture.

The required system capabilities to achieve the given goal are called key performance attributes (KPAs). To fulfill those KPAs, the solution specific function, or the top functionality that is used to build the architecture, is decomposed into lower level functionalities. By recursively applying the function goal reasoning, all higher-level functions can be decomposed down to the manageable granulation. The highest level functional parameters in the decomposition are called measure of effectiveness (MOEs). MOEs are determined by the relationships to and performance of the immediate lower level functional parameters which are defined as measure of performance (MOPs). Those MOPs are the resultant of other even lower level functional parameters called technical performance measures (TPMs).

With the rapid advancement of technologies in recent years, the architectures of today's products have become inherently complex. It usually consists of highly interrelated, interconnected, or interwoven entities. In addition, due to the trend of seeking the best value of product and bettering life at minimum cost with maximum satisfaction, this complex architecture needs to be changed or extended all the time to find new competitive advantages in rapidly changing market.

The architecture extension can be realized either by adding new functional requirements to the existing architecture or introducing new metrics to measure additional performance of the architecture. On one hand, to achieve new functional requirements, the additional functions need to be divided down to the manageable granulation like existing architecture. Then, it is required to correlate newly developed functional parameters with all other existing ones at each level of the architecture. The performance of the extended system depends on the effect of internal correlation among all functional parameters in the extended architecture. On the other hand, when new performance metric is needed, the introduction of new metric for each functional parameter at each level along its value pathway can measure the system capability of new architecture.

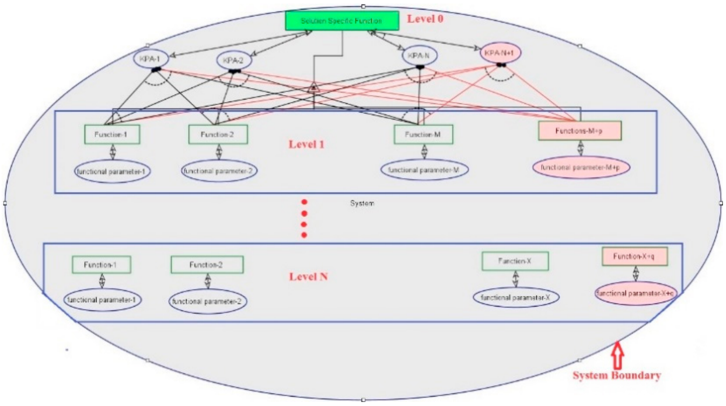

Fig. 1. Extended architecture generation

The Fig. 1 is an illustration of a generalized representation of extended architecture. To evaluate the solution specific function shown in Fig. 1, the architecture is assessed at its boundary using n different KPAs. The architecture is further extended by an additional functional requirement, which is denoted as KPA $n+1$. To fulfill the requirement of this additional KPA, p new functions are introduced at the lower level, i.e., Level-1, of the architecture. All new functions are then kept being decomposed until level N. With each function, there is also a corresponding functional parameter at each level of the architecture. Their interrelationship at different levels will determine the whole system capability at the boundary of the system.

Although extension of existing architecture in product design is increasingly important in today's competitive world, research that can be used to guide such an extension and assess the performance of post-extension has been less focused. Most existing literature in architecture modeling for design is focused on the assessment of top level attributes specifically based on KPAs. For example, Pape et al. described an evaluation method for assessing a range of system of systems (SoS) meta-architecture alternatives by defining the fuzzy concepts and establishing rule sets for the overall SoS [2]. Renault presented an assessment model specifically for unmanned aerial vehicle (UAV) systems [3]. This model assesses the probability of generated architecture meeting performance as well as capability requirements. Rodano and Giammarco generated a formal representations of a well-defined system architecture and showed how these representations can be used to evaluate an instantiated system architecture to determine whether it is well formed or not [4]. Xu et al. presented a fuzzy logic based method for Failure Mode and Effect Analysis for quality assurance and reliability improvement, interdependencies among various failure modes with uncertain and imprecise information [5]. G. Muller proposed an approach for the selection of alternative architectures in a connected infrastructure system to increase resilience of the overall infrastructure system [6]. Renault and Dagli described an integrated method to assess SoS meta-architecture utilizing the genetic algorithm optimized KPAs and the Mamdani-type rule based fuzzy inference system [7]. Also, Renault outlined dual application of rule based fuzzy inference systems for the SoS meta-architecture assessment [8].

It can be seen that very limited existing research can completely describe the whole process of generation and evaluation of new architecture. Consequently, the existing model cannot find the interrelationship among the functionalities and sensitivity of each functional parameter to the architecture.

For the extended architecture, it is important to build such an interrelationship among the new functional parameters and/or between new and existing parameters. This relationship can determine the performance of the newly built architecture regarding completeness, integrity, consistency, usability, and compliance. Thus, a comprehensive model for generating an extended architecture and assessing it along its value pathway from lowest level functional parameters to KPAs is needed to help product designers guide the possible changes in the architecture that would increase stakeholder acceptance, decrease defects/costs, and enhance system performance and quality throughout the entire product lifecycle [9].

In this paper, we propose a general algorithm for assessing product architecture performance considering architecture extension. To better illustrate the whole picture of new architecture generation and assessment, a hypothetical automobile cooling system is considered. The existing architecture is built upon four KPAs: cooling capacity, heat exchange effectiveness, affordability, and modularity. The architecture is then extended. Finally, new architecture performance value is determined by assessing all the architectures.

The rest part of the paper is organized as follows. Section 2 represents extended architecture generation from existing architecture using a hypothetical automobile cooling system. Section 3 demonstrates the proposed multiple fuzzy assessment model. Finally, conclusions are drawn and future research opportunity is discussed in Section 4.

2. Extended architecture generation from existing architecture

The architecture of the hypothetical automobile cooling system is a moderate level complex system. The functional goal behind the generation of this hypothetical architecture is "to cool automobile engine". Fig. 2 shows the level-3 architectural decomposition of the system after using modularization techniques.

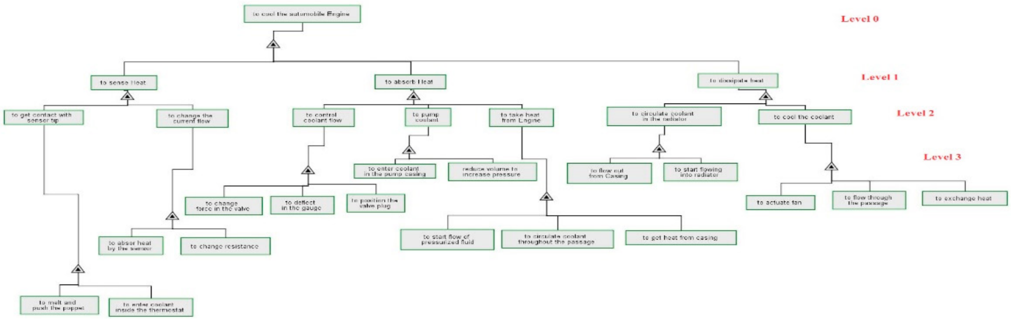

Fig. 2. Level-3 functional decomposition of hypothetical automobile cooling system

The existing architecture is further extended in two ways: the first extension is represented by introducing the functional parameter "online monitoring system"; and the second one is realized by adding a new performance metric "reliability".

On one hand, the “online monitoring” function is first decomposed to the manageable granulation function at the lower levels. After that, the relationship matrix between existing functional entities and the functions derived from decomposition of this new functional parameter needs to be built. The matrix building starts from the relationships between TPMs and MOPs, then MOPs and MOEs, and finally MOEs and KPAs. Table 1 is an example of a generalized relationship matrix between TPMs and MOPs when new functional parameters extend the architecture. New TPMs and MOPs required to fulfill the new functional parameter are added to the relationship matrix. Note that, there is no need to build any new relationship matrix since there is no new performance metric introduced to the existing architecture. Table 2 explains the abbreviation of the relationships and the corresponding interaction score used in Table 1.

Table 1. Relationship matrix between TPMs and MOPs (architecture extended by new functional parameter)

	MOP-1	MOP-2	….	….	MOP-N	MOP (new)	….
TPM-1	PP	NR	….	….	….	WP	….
….	NR	….	….		….	NR	….
TPM-N	WN	PN	….	….	….		….
TPM (new)	NR	PP	….	….	….	PP	….
….		….	….	….		….	….
Overall Relationship	∑ Relationship, RR	….	….	….	….	….	….

Table 2. Interaction score and symbols

Relationship	Symbols	Interval	Relationship	Symbols	Interval
Perfectly Positive	PP	3-5	Weakly Negative	WN	-(1-2)
Weakly Positive	WP	1-2	Perfectly Negative	PN	-(3-5)
No Relationship	NR	0	Resultant Relationship	RR	∑All relationship

Employ the same format and notations, the relationship matrix between MOPs and MOEs, MOEs and KPAs can also be generated. Each relationship matrix will be used to cluster those new functional entities decomposed from the new functional parameters (online monitoring system) by minimizing the interactions across modules and maximizing internal coherence within modules of the extended architecture so that new entities will be connected to the existing system.

On the other hand, when the new performance metric “reliability” is added, it will be determined by introducing and measuring the new performance metric at each level of functional parameter of the architecture. This new performance KPA (reliability) along with the previous KPAs will ultimately measure the system effectiveness. Table 3 shows the additional relationship matrix between TPMs and MOPs when new performance metric extends the architecture. This additional matrix along with the existing ones will build the new extended architecture. The number of additional matrices will be proportional to the new performance parameters. Note that, in this extension, no new TPMs and MOPs need to be added since no additional functional parameter is assessed.

Table 3. Relationship matrix between TPMs and MOPs (architecture extended by new performance metric)

	MOP 1	MOP 2	….	….	MOP N
TPM 1	PP	NR		….	….
….	….	….	….	….	….
TPM N	WN	PN	….	….	….
Overall Relationship	∑ Relationship		….	….	….

Using the relationship matrix and same clustering techniques, proper functional decomposition for the extended architecture of hypothetical automobile cooling system is obtained. The extended architecture and “from function to form” mapping based on the decomposition is shown in Fig. 3. Object Process Methodology (OPM) is used for the architecture illustration to capture inherent relationship between form and function.

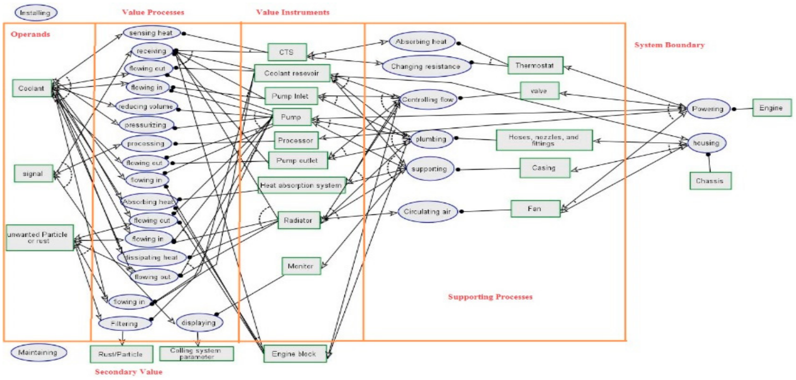

Fig. 3. Extended architecture of the hypothetical automobile cooling system (new functional parameter “Online monitoring system” extends the architecture)

3. Proposed model for architecture assessment

Important functional, logical and operational interdependencies are often overlooked by the existing modeling approaches [10, 11]. To address this concern, in this section, a level by level architecture generation and assessment tool using fuzzy logic that can completely reveal ambiguity, help the architect to configure each block, and build a successful architecture is proposed as shown in Fig. 4. The functional parameters at each level is denoted by the notation $FP_x - i$, where x denotes the level and i=1, 2, …, N is the index of the parameters in each group.

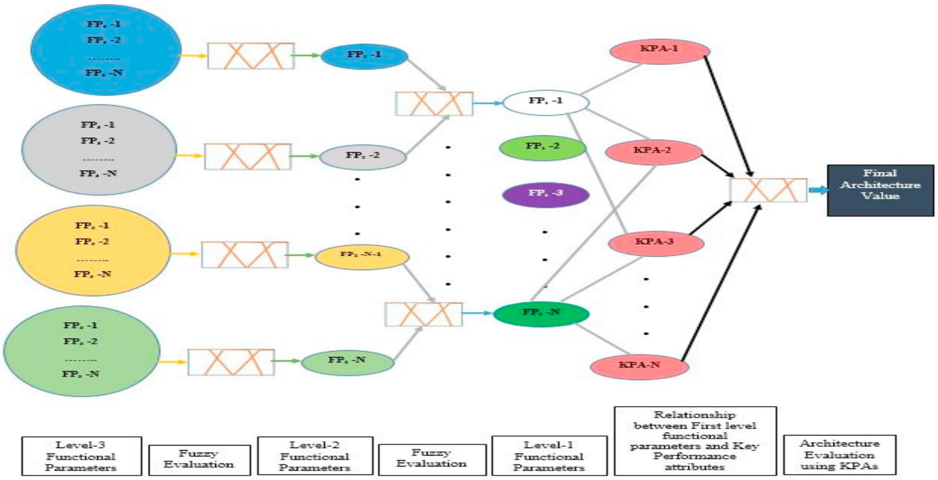

Fig. 4. Proposed multiple fuzzy model

Since the lowest level is the building block of the entire architecture, the proposed architecture assessment starts from the lowest level to make the assessment easier, the evaluation better, and the correlation greater. This architecture assessment model is useful for any number of KPAs. As the evaluation model begins from the unit level of architecture and integrates all functional parameters of each cluster, it will be easy to assess the effect of each possible change inside the architecture. Moreover, any new metric or functional parameter can be easily incorporated with the existing assessment parameters. Thus, the proposed assessment model can be considered a generalized assessment model for any new architecture as well as the extended architecture.

3.1. Choosing membership functions

Fuzzy logic based evaluation technique is used in this model because of the capability to converse, reason, and make rational decisions in an environment of imperfect information such as imprecision, uncertainty, and incompleteness of information, conflicting information, partiality of truth, and partiality of possibility. It is important to choose the appropriate membership function to describe all the information incorporated in the fuzzy set. The shape of the most accepted membership functions are piecewise linear functions (with restrictions), Gaussians or Sigmoids [12]. For inferencing this multiple fuzzy model, trapezoidal membership function is used. It is normalized, convex, and asymmetric. The trapezoidal membership function chosen for this problem is shown in Fig. 5. The range of the membership functions are generally set according to the requirement of the system. In this case study, it is set based on some criteria of the cooling system, e.g., cooling capacity, heat exchange effectiveness [13], [14].

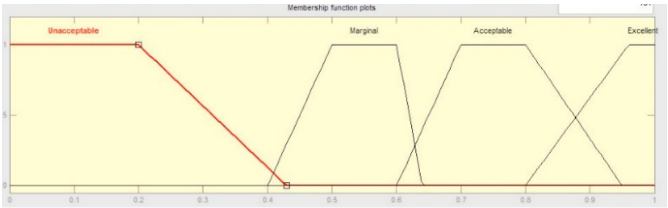

Fig. 5. Membership function

3.2. Establishing the fuzzy rules

In this section, fuzzy mapping rules are established between the input and the output using linguistic variables. The foundation of those rules is the fuzzy graph and inherent relationship depending on the human intuition or insight focusing stakeholder's requirements. The Table 4 shows the fuzzy rules for the fuzzy inference system of the virtual "Automobile Cooling System" considering the additional KPA "reliability" with the existing four KPAs:

Table 4. Fuzzy rules used for the fuzzy inference system considering new KPA "reliability"

Number	Linguistic rules	MATLAB rule editor
1	If any one of the attributes falls in unacceptable, then whole architecture will be unacceptable	**If** (cooling capacity is unacceptable) or (heat exchange effectiveness is unacceptable) or (modularity is unacceptable) or (reliability is unacceptable) or (affordability is unacceptable) **then** (architecture is unacceptable)
2.	If all are excellent then the whole architecture will be excellent	**If** (cooling capacity is excellent) and (heat exchange effectiveness is excellent) and (modularity is excellent) and (reliability is excellent) and (affordability is excellent) **then** (architecture is excellent)
3.	If all are marginal, then the whole architecture will be unacceptable	**If** (cooling capacity is marginal) and (heat exchange effectiveness is marginal) and (modularity is marginal) and (reliability is marginal) and (affordability is marginal) **then** (architecture is unacceptable)
4.	If all are acceptable then the whole architecture will be acceptable	**If** (cooling capacity is Acceptable) and (heat exchange effectiveness is acceptable) and (modularity is acceptable) and (Reliability is acceptable) and (affordability is acceptable) **then** (architecture is acceptable)
5	If any one of the attributes will be marginal and all other excellent then whole architecture will be marginal.	**If** (cooling capacity is excellent) and (heat exchange effectiveness is excellent) and (modularity is excellent) and (reliability is excellent) and (affordability is marginal) **then** (architecture is marginal)
		If (cooling capacity is excellent) and (heat exchange effectiveness is excellent) and (modularity is excellent) and (reliability is marginal) and (affordability is excellent) **then** (architecture is marginal)
		If (cooling capacity is excellent) and (heat exchange effectiveness is excellent) and (modularity is marginal) and (reliability is excellent) and (affordability is excellent) **then** (architecture is marginal)
		If (cooling capacity is excellent) and (heat exchange effectiveness is marginal) and (modularity is excellent) and (reliability is excellent) and (affordability is excellent) **then** (architecture is marginal)
		If (cooling capacity is marginal) and (heat exchange effectiveness is excellent) and (modularity is excellent) and (reliability is excellent) and (affordability is excellent) **then** (architecture is marginal)

Similarly, the fuzzy rules are developed for the fuzzy inference system of the virtual “Automobile Cooling System” considering the additional function “online monitor system” to assess the performance of new architecture.

3.3. Fuzzification

Among the two fuzzy inferencing methods (Mamdani method [15] and Takagi Sugeno Method [16]), Mamdani method is applied in this paper because of its widespread acceptance and more intuitive, human like manner. Simple structure of 'min-max' operations entails the computational burden and produce acceptable result. Using MATLAB fuzzy toolbox 2016a, the fuzzy inference system for the extended automobile cooling system is generated and it is presented in the Fig. 6:

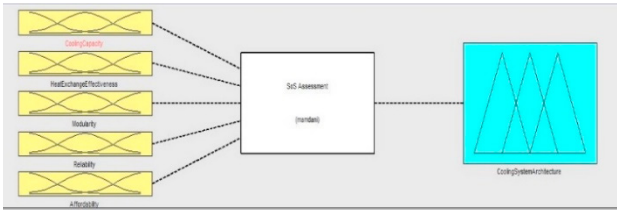

Fig. 6. Fuzzy inferencing of the hypothetical automobile cooling system

3.4. Defuzzification

Using center of gravity method, the defuzzification process converts the architecture assessment value to a crisp value. Table 5 shows the comparison of assessment values between the existing architecture and the extended new architectures.

Table 5. Comparison between existing and extended architectures

Architecture	Architecture Assessment Value
Existing architecture	0.94
Architecture extended by additional performance metric “reliability”	0.87
Architecture extended by new functional requirement “online monitoring system”	0.90

The architecture assessment value depends on each internal relationship among functional parameters. When the new performance metric “reliability” extends the architecture, the capability of the extended architecture declines. This may happen due to the poor performance regarding reliability from the existing functional parameters.

Developing new form of architecture to perform more reliable functionality can increase the architecture value. However, there may exist some KPAs, like affordability, that are inversely related to it. Therefore, a trade space can be generated along with the creation of every new architecture. Optimum architectural value can be achieved by finding the best trade off among various KPAs.

Similarly, adding a new functional parameter of online monitoring system makes the existing system more complex. To maintain the performance of the architecture, each new functional parameter should have the same capability as existing functional parameters. Otherwise, it will also degrade the architecture performance.

Sections 2 and 3 illustrate the process of extended architecture generation and assessment for additional functional parameter of “online monitoring system”, and performance parameter of “reliability” for an automobile cooling system. It provides a generalized algorithm/procedure that is applicable to generate and assess architecture for any number of new functional and performance parameters in complex product architecture design as follows: 1) building new or modify existing relationship matrices based on the requirements either “new performance parameter” or “new functional parameter”, 2) identifying the correct decomposition for the new architecture, 3) setting the value of membership function and establishing fuzzy rules according to the requirements, 4) assessing the performance of new extended architecture and comparing to the previous ones.

4. Conclusion and future work

In this paper, the hypothetical automobile cooling system architecture is generated and extended by two possible ways. The proposed generalized multiple fuzzy model is used to evaluate all the architectures. This flexible and comprehensive model can be an effective tool to generate and assess any kind of complex and extended product architecture in cyber physical system logically and conveniently.

For future work, genetic algorithm technique can be applied to find the best KPAs. Architecture-based multi-objective optimization for trade space exploration is required to identify the resource allocation strategy for ensuring the best trade-off among optimization objectives. Type-2 fuzzy can be studied to handle more uncertainty associated with the system to enhance the model robustness, deal with more uncertainty, and assess the whole architecture more reliably as well as precisely.

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