Availability Allocation Using Systems Engineering Principles

Abraham Almaw Jigar, Cecilia Haskins and Mary Ann Lundteigen
Department of Production and Quality Engineering
Norwegian University of Science and Technology
Trondheim, Norway
abraham.a.jigar@ntnu.no, cecilia.haskins@ntnu.no, mary.a.lundteigen@ntnu.no

***Abstract*—Availability is one of the key performance indicators for repairable systems, usually expressed as the average proportion of time the system is in a state capable of performing the required function. Availability can be enhanced by increasing the reliability and/or reducing the restoration time of components. In the design phase, a mathematical method is applied to optimize the availability improvement (or target) at the component level with some relevant constraints such as cost and complexity. This paper is a continuation of the work carried out by the authors to address such mathematical aspects. System design is a multidisciplinary activity subject to "conflict of interest" among stakeholders such as system integrator, equipment supplier, and operator. The focus of this paper is to extend the previous work by looking into availability allocation from the perspective of systems engineering. Systems engineering is a systematic approach to enable the realization of a successful solution. The paper uses a systems engineering methodology to demonstrate its applicability as an integral part of the availability allocation process. The conclusion is that a systems engineering methodology can be applied successfully such that the system availability target and the stakeholders' needs can be met.**

Keywords—Availability allocation; Allocation method; Systems engineering; Repairable systems; Stakeholders

I. INTRODUCTION

Availability is a useful performance indicator for repairable systems, usually expressed as the average proportion of time the system is in a state capable of performing the required function [1]. In the early design phase of a new product development or modifying an existing one, availability is calculated to estimate the performance of the system and to check whether the target/requirement is met. Availability, in its simplified form, is a function of reliability and restoration time. If a design solution does not meet the required availability target, an improvement can be found through increasing the reliability of components and decreasing their restoration time. To achieve the improvement with a minimum effort (or cost), an availability allocation method can be used [2-5].

Availability allocation is an iterative process that involves both objective judgments (e.g., component performance from reliability data) and subjective judgments (e.g., operational and maintenance philosophies and other decisions from stakeholders). Developing a complex system involves a number of stakeholders and some stakeholders may have the power/urgency to influence availability improvement alternative solutions [6]. Whether or not an improvement alternative is optimal may depend on both the level of effort the solution would require *and* whether it would meet all stakeholders' needs throughout the lifecycle of the system. The former is an optimization problem and a number of availability allocation methods have existed and used for many years [7]. The previous work by the authors of this paper [5] addressed the mathematical aspects of availability allocation. For complex systems, such as subsea production and processing systems, the availability allocation process needs a systematic (qualitative) approach along with mathematical methods to take into account stakeholders' needs. To this end, the purpose of this paper is to introduce a systems engineering method that enables the analyst to look holistically at the availability improvement process [8].

Despite the popularity in industry and academia, there is no a generally accepted definition for systems engineering, and people use the term differently from the perspective of their expertise [9]. In this paper, we suffice with the definition provided by International Council on Systems Engineering [10], "an interdisciplinary approach and means to enable the realization of successful systems". Fruitful efforts by specialized areas/departments at lowest levels and in the integration of them to form a whole will bring about a successful solution. In our case, the reliability engineer, who is responsible for the availability allocation process, is to implement a systems engineering method/thinking to bring about a successful system/solution (with respect to system availability). But, the reliability engineer as a system engineer does not own the allocation problem or the solution but is the enabler [8] who makes sure the system meets the "stakeholders' needs in a high quality, trustworthy, cost efficient and schedule compliant manner" throughout the system design and development process [10].

Many systems engineering methods have been proposed since the early 70's with general agreement on the tasks they considered relevant. The SIMILAR process is originally developed by extracting common tasks from several systems

© IEOM Society International

engineering methods and is comprised of seven tasks [11]. These are presented below with their description (quoted from [12]):

1. *State the problem.* Stating the problem is the most important systems engineering task. It entails identifying customers, understanding customer needs, establishing the need for change, discovering requirements and defining system functions.
2. *Investigate alternatives.* Alternatives are investigated and evaluated based on performance, cost and risk.
3. *Model the system.* Running models clarifies requirements, reveals bottlenecks and fragmented activities, reduces cost and exposes duplication of efforts.
4. *Integrate.* Integration means designing interfaces and bringing system elements together so they work as a whole. This requires extensive communication and coordination.
5. *Launch the system.* Launching the system means running the system and producing outputs -- making the system do what it was intended to do.
6. *Assess performance.* Performance is assessed using evaluation criteria, technical performance measures and measures -- measurement is the key.
7. *Re-evaluate.* Re-evaluation should be a continual and iterative process with many parallel loops.

Accordingly, a systems engineering process starts with identifying customers' needs and goes through tasks from 1 to 6 in an iterative manner with continuous Re-evaluation at each step until the product/ system lifecycle is completed (Fig.1). Although SIMILAR provides a good overall insight on what a systems engineering method entails, it is not quite suitable for availability allocation process. Because, while the availability allocation process is performed primarily in the design phase, the SIMILAR spans from "cradle to grave/rebirth".

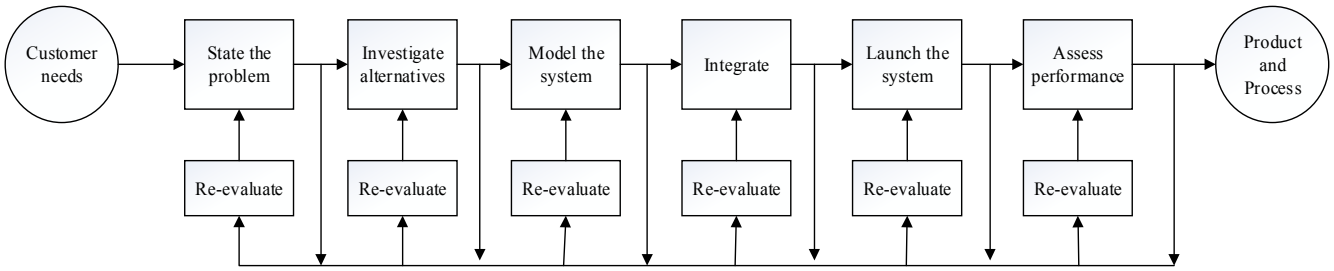

Fig.1. The SIMILAR framework [11]

Haskins [8] provided a breadth and depth overview of systems engineering methods, including SIMILAR. The author identified 38 activities from the twelve most often-cited methods. Following a detail analysis, a simple and jargon-free method, called SPADE emerged with the intention that it can be applied without requiring years of systems engineering training. This makes the method suitable for our purpose as availability allocation is normally carried out by reliability engineers. SPADE is an acronym for Stakeholder (i.e., identification of stakeholders and recognition of their importance and needs), Problem formulation, assessing Alternatives (or Analysis), Decision-making and Evaluation. Like SIMILAR, the method conveys, as shown in Fig.2, that the realization of a successful system/solution is an iterative process comprising a careful evaluation at each step/milestone. Parallel to SPADE, Haskins [13] proposed a 6Cs meta-framework, i.e., Communication, Comprehension, Continuity, Collaboration, Cooperation and Coordination. The intent of 6Cs meta-framework is to complement the SPADE method. Because systems engineering addresses problems in interdisciplinary and iterative manner, these 6C attributes are essential to enable the work of systems engineering. The 6Cs are essential but not discussed in this paper and reference is made to [13].

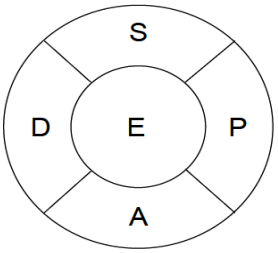

Fig. 2. The SPADE framework [8]

This paper demonstrates the application of the SPADE method in the availability allocation process alongside the application of the availability allocation method proposed by Jigar et al. [5]. Therefore, attributes associated with the SPADE method in this paper are delimited within the context of the applied availability allocation method, i.e., the method in [5]. The outline of the paper follows the SPADE method after introducing the fundamentals of the availability calculation in Section II. Section III discusses stakeholder identification and problem formulation activities. These activities are followed by Alternatives, presented in Section IV, to choose an alternative solution that addresses the formulated problem having the aim to meet the identified stakeholders' needs. Activities associated with decision-making and evaluation are presented in Section V. Finally, Section VI presents some concluding remarks and indications for further research work.

II. AVAILABILITY CALCULATION

Because availability has different meaning and interpretation for safety systems and production systems, it is important to distinguish them here. Most safety systems are dormant and are required to perform their function upon demand. Part of the failures is hidden and is revealed only during regular proof testing [14-16]. As a result, the availability formula for safety systems is different from production systems, as failures in a production system reveal themselves immediately when the system stops or shows some kind of state transition. The focus of this paper is only on production systems, such as subsea production and processing systems.

In order for the design of such systems to meet the availability target, the restoration activities throughout the system lifecycle including the availability, needs, and requirements of the stakeholders who are performing restoration activities should be taken into account. Fig. 3 demonstrates the main activities required to put a subsea production and processing system back to normal operation upon a critical component failure. Four main locations are shown: (i) where the system is operating (subsea), (ii) service base located onshore where capital spares are placed and minor refurbishment and test activities are carried out and, (iii) component supplier (depending on the component it may be located outside the country) where major refurbishment activities are carried out, and (iv) where the intervention vessel(s) is located, which is not often static unless dedicated vessel(s) is available. When a failure occurs, the vessel is sent to the service base to pick-up the spare and, at the same time, the test activity at the service base initiates, since it is "risky" to put a spare into operation without proof testing. When the test activity is completed and the vessel arrives, the spare is transported to the site and the component replacement activity initiates immediately. The elapsed time until the system is restored is referred to as restoration time. Now, the service base lacks one spare. As sparing has an impact on the availability of the system (i.e., if a like component fails before the failed one is restocked) the time required to refurbish the failed component needs to be considered. Depending on the severity of the failure, the refurbishment can be performed at the service base or at the supplier's workshop. Thus, refurbishment time is the period from when the module is retrieved from the service based until it is restocked.

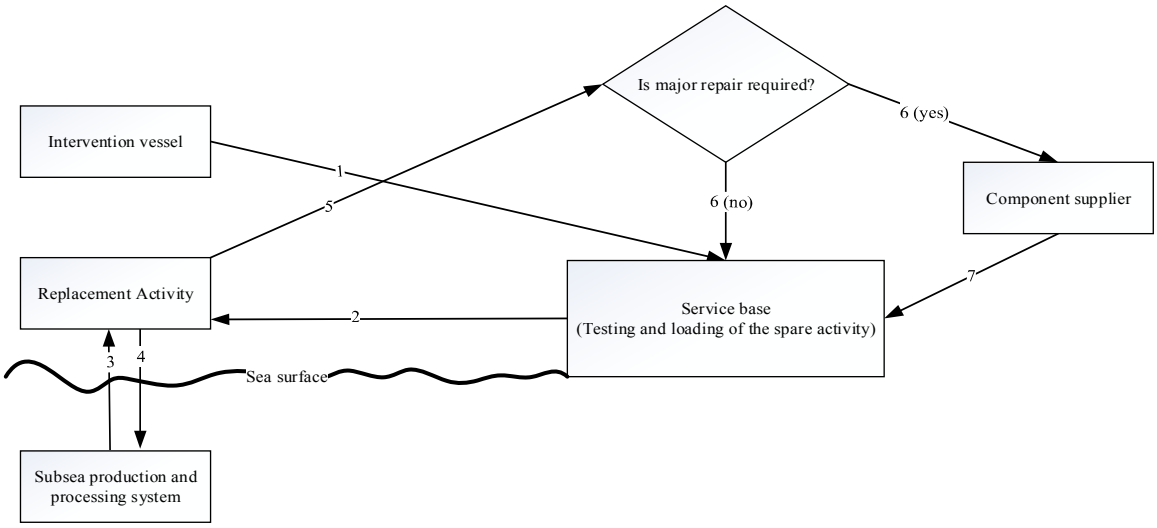

Fig. 3. Main activities considered in availability calculation

Availability (A) of a component is a function of time to failure and the time needed to put the component back to operation after failure [1]. The (average) time required to put a component back to normal operation is referred to as mean time to

restoration (MTTR), which covers all technical and logistic activities. The steady state availability for component i will then be

$$A_i = \frac{\text{MTTF}_i}{\text{MTTF}_i + \text{MTTR}_i} \quad (1)$$

where mean time to failure (MTTF) and MTTR are assumed to be exponentially distributed with rate λ_i and μ_i. For tractability purpose, it may also be reasonable to assume that the system comprises n independent components connected in series and all components are equally critical for the (un)availability of the system. The assumption of series architecture may stem from the fact that the allocation is performed in the early design phases where a detail system architecture is not yet available. Further, since the assumption is that each component is equally critical for the system, the probability that the system is functioning given one out of n components failure is zero. Hence, the system availability is

$$A = \prod_{i=1}^{n} \frac{\text{MTTF}_i}{\text{MTTF}_i + \text{MTTR}_i} = \prod_{i=1}^{i=n} \frac{\mu_i}{\lambda_i + \mu_i} \approx \left(1 + \sum_{i=1}^{n} \sigma_i\right)^{-1} \quad (2)$$

where $\sigma_i = \lambda_i M_i$ can be regarded as the current unavailability contribution of component i, and for brevity purpose M is used instead of MTTR. This availability formula is referred to as inherent availability or design-in availability [4], and a solution based on this method is high-level in the sense that the allocation is carried out by improving the MTTF and MTTR without detailing how.

III. Identification of Stakeholders and Problem Formulation

Identification of stakeholders is dependent on how the engineer perceives the problem and how s/he intends to solve it [17]. It is thus important that the system provider first understands the problem well from different perspectives. According to Fet [18], a systems engineering process begins with identifying the needs, which is carried out by answering three questions: 1) What is needed? 2) Why is it needed? 3) How may the need be satisfied? As pointed out by Haskins [8], there is an overlap between stakeholder identification and problem formulation tasks and these two can be performed in parallel. Therefore, in the following, we will address the problem formulation in Section A, based on this, stakeholder identification and mapping of availability improvement constrains to the identified stakeholders will be presented in Section B, and, finally, "how may the [stakeholders'] needs be satisfied?" will be discussed in Section C.

A. What is needed? Why is it needed?

In the early design phase, design and operational concepts should be assessed carefully so that stakeholders' needs can be understood and achieved. Where availability improvement is necessary, e.g., when the availability target is not met, engineers are challenged by how the necessary improvement can be translated down to the level of component reliability and restoration time with a minimum cost. The target is generally set out by the owner of the system and the system integrator/designer strives to translate the target into component level with minimum cost and effort [2]. The first step perhaps would be to breakdown the system design (or concept) to module, subsystem, item, element or components level, depending on the progress of the system design process. Fig.4 illustrates the translation of system availability target (i.e., expressed as the proportion of time the system is available for production) down to component reliability goals and restoration time goals.

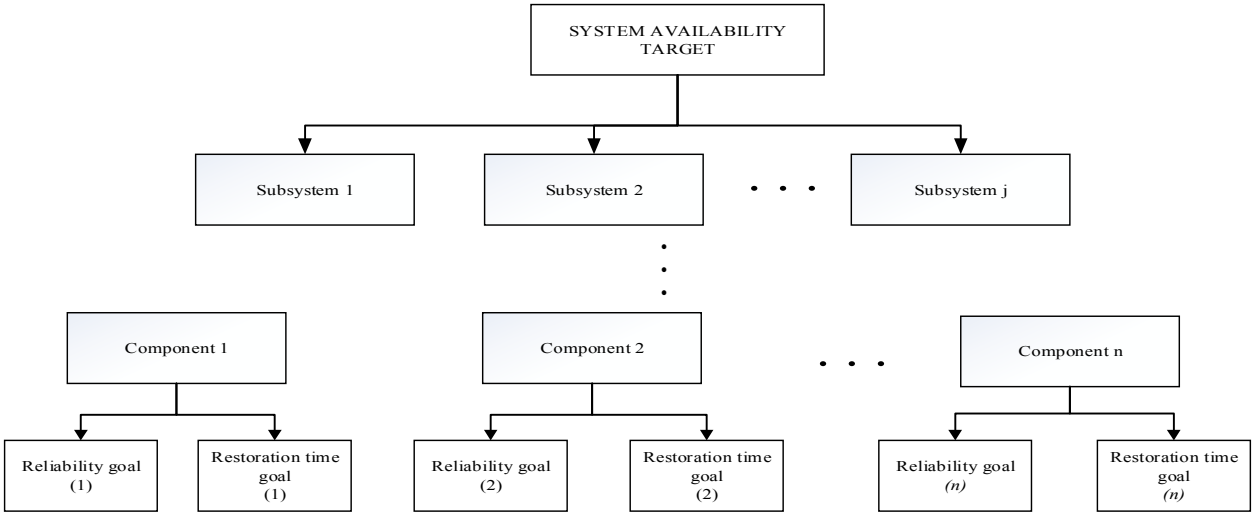

Fig.4. System breakdown

The problem can mathematically be formulated as follows: If A^t be the availability target and σ_i^a be the allocated unavailability contribution of component $i, i = 1, \cdots, n,$ then the allocation problem can be stated as [5]

$$\begin{aligned} &\text{Min} \sum_{i=1}^{n} f_i(\sigma_i, \sigma_i^a) \\ &\text{Subject to} \left(1 + \sum_{i=1}^{n} \sigma_i\right)^{-1} = A^t \end{aligned} \tag{3}$$

where f_i is the cost or complexity function to reduce σ_i to σ_i^a.

B. Stakeholders identification

According to the stakeholder framework suggested in [6], stakeholder identification attributes can be seen from three non-mutually exclusive perspectives: power, legitimacy, urgency. A stakeholder possesses one or more of these attributes, but, in a general context, we can see stakeholders as those who directly or indirectly affect or are being affected by the system during its lifecycle [19]. As mentioned, high availability can be achieved by increasing the reliability (preferably) and/or decreasing the restoration time of components. Reliability can be increased through high-reliability components and/or high level of redundancy [20]. Restoration time is dependent on the time required to make maintenance supports readily available to perform the repair/replacement activity (i.e., logistics such as spare, maintenance crew and their mobilization) and the time required to perform the actual repair/replacement activity (Fig. 3). To reduce the restoration time the following options can be considered:

- minimize warehouse-testing time: Spares often need a proof-test before they are mobilized to replace a failed module. The duration can be minimized through, for example, increasing the test and refurbishment frequency of spares while in the warehouse, increase the crew size to perform the test upon demand as well as improving concurrency.
- minimize logistic delays, such as spare and vessel/rig mobilization times, and other administrative delays.
- improve spare availability through acquiring sufficient amount and/or minimizing lead-times.
- minimize module replacement time, for example through effective modularization, increasing crew size and improving concurrency.

Preventive maintenance may also have a positive impact on reliability but it improves reliability at the expense of availability. Determining preventive maintenance schedule and cost to maximize the availability is an optimization problem per se [21].

Considering a subsea production and processing system, Fig. 5 illustrates some of the identified stakeholders and their interactions. The system integrator is obliged to provide the system with a statistical evidence about the availability

performance of the system as specified by the operating company. These two parties, namely system integrator and operating company, can be considered primary stakeholders. Because some design and operational specifications should be in-line with government regulations, the society/government also is regarded as primary stakeholder. Further, the reliability data for the availability calculation is obtained from equipment suppliers, and the restoration time data mainly from the operating company. As mentioned, restoration time is impacted by service providing companies such as vessel suppliers. Therefore, companies such as an equipment supplier and service provider are considered secondary stakeholders. The figure indicates also the iterative process of availability allocation, which can be related to the SPADE method depicted in Fig.2.

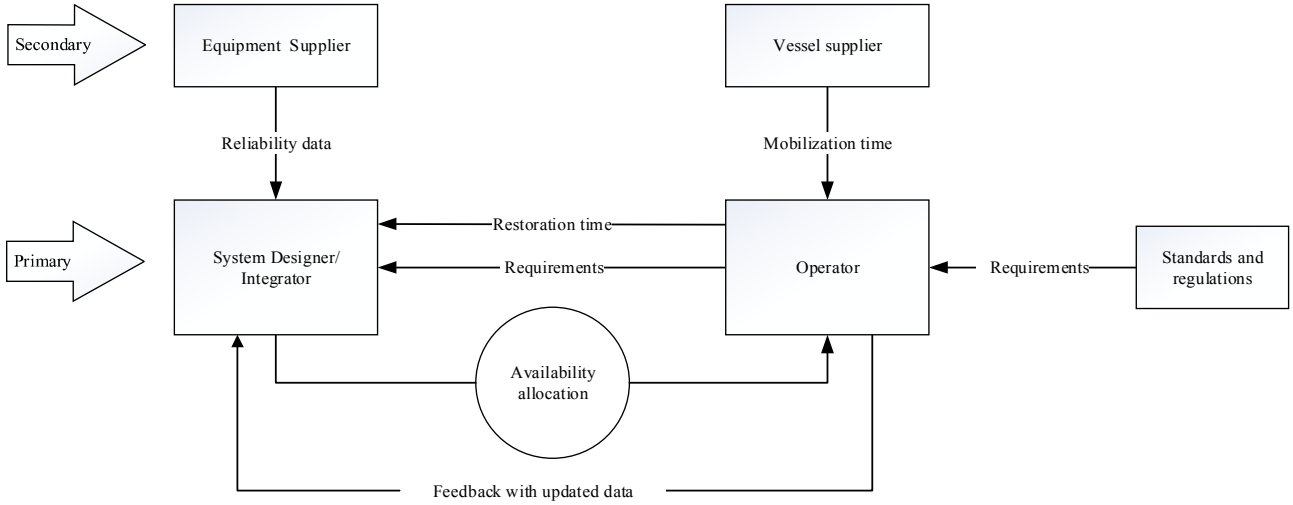

Fig. 5. Relationship among main stakeholders

Once stakeholders are identified, their needs should be recognized and followed-up throughout the lifecycle of the system. Care should be taken when new stakeholders are identified with their own needs and perhaps with an alternative solution as it may cause "conflict of interests" with existing ones. The following can serve as examples for stakeholders' needs.

- No more than one restoration activity in 5 years associated to component X
- The availability improvement cost for the system should not be greater than $1.5M
- Total maintenance cost during the system's mission time should not be greater $100M
- No reliability improvement should take place on component X

Part of the problem formulation and recognizing stakeholders' needs is to map the availability improvement options, opportunities and constraints to the relevant stakeholders (Fig. 6). To demonstrate the mapping, consider any single component from Fig. 4. As mentioned, the preferred availability improvement route is through built-in reliability, which can be performed through one of the following options: purchasing a commercially available component that is more reliable than the currently available one, introducing redundancy or carrying out a reliability development program [20]. This improvement route is related to capital expenditure (CAPEX), primarily performed by the system integrator although it is of high interest to the operating company. The other route is through restoration time (and preventive maintenance), which is an operational expenditure (OPEX) and is of primary concern to the operating company. The aim of this mapping is to generate alternatives to improve the availability of a component, with the associated estimates for improvement cost as input to the availability allocation model.

C. How may the need be satisfied?

In order to protect the Evaluation from being flexible and situation-dependent, measures of effectiveness (MOEs) need to be stated in unambiguous and measureable manner during problem formulation. MOEs are standards against which the "goodness" of the solution may be assessed [22], and are directly related to the objective, purpose or target of the system under consideration. MOEs can also be seen as measure of performance and success criteria for evaluating the progress and achievement of the process that brings the system into being [8]. Although they are somehow subjective to the stakeholder who has the right to set or influence the criteria, MOEs measure the quality that stakeholders' needs are to be met, or, simply, the quality of the solution. An example of a MOE can be that the confidence of attaining the availability target with minimum

cost (proposed by the solution) should be greater than 95%. As can be noticed, MOEs affect the decision on "How may the need be satisfied?" i.e., the type of availability allocation method (Alternative) that needs to be applied.

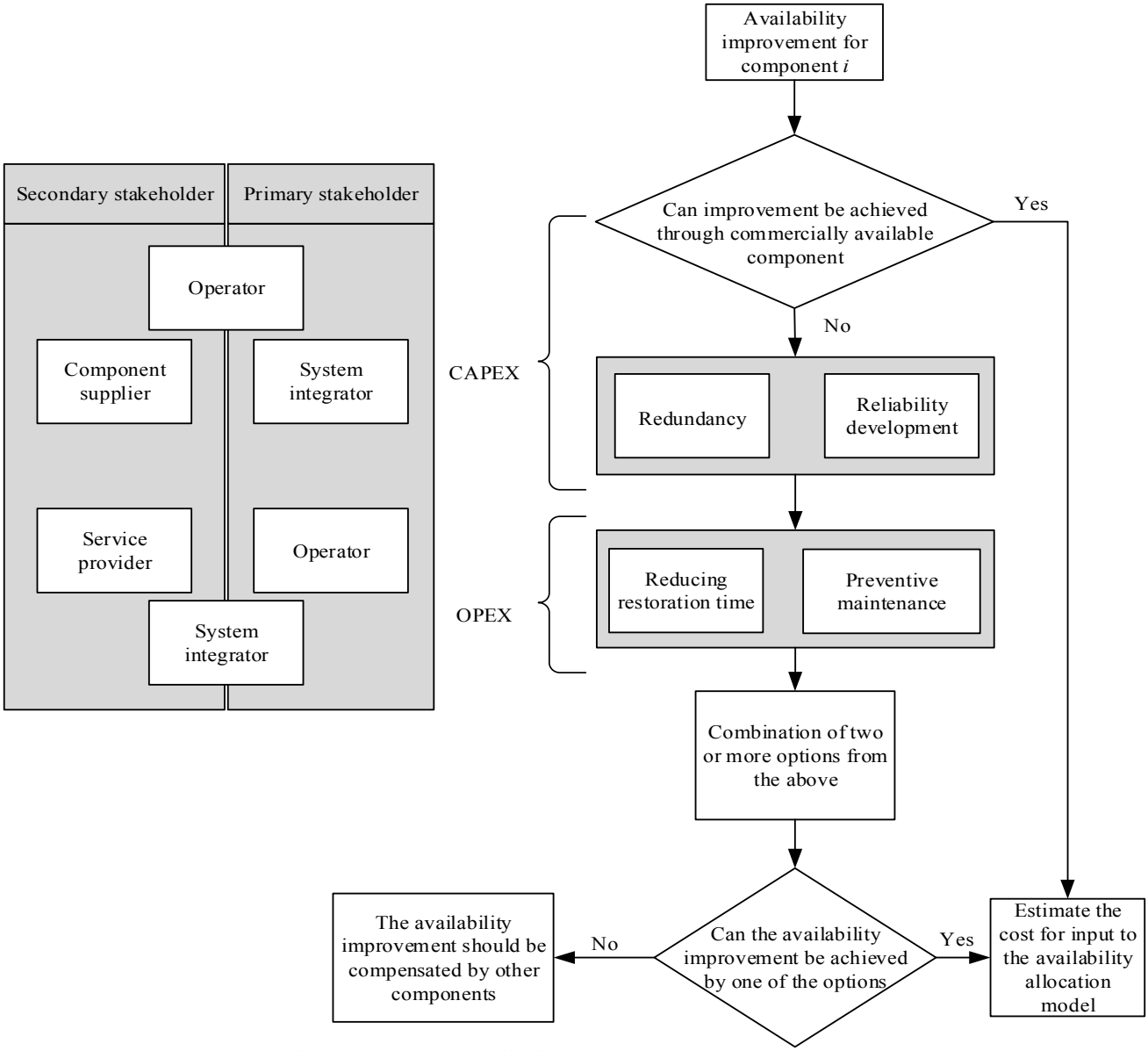

Fig. 6. An illustration for mapping availability improvement options to the relevant stakeholders

IV. ALTERNATIVE

During problem formulation, stakeholders may propose alternative solutions to address the problem [8]. However, these alternative solutions should be analysed for optimality in the sense that stakeholders' needs and MOEs are met [18]. Availability allocation methods have existed for several decades with varying degrees of complexity [7]. Jigar et al. [5] argue that in the early design phase simple and intuitive allocation methods are more practical than mainstream allocation methods. Consequently, the authors proposed a new method that is adopted from a well-known reliability allocation method, i.e., minimum effort algorithm. In this paper, as a continuation of Jigar et al. [5], we suffice with describing the procedure by which the allocation is performed and for detail discussion of the method reference is made to the article.

A. Allocation procedure (cost based)

1. Arrange the current unavailability contributions in descending order, i.e., $\sigma_1 \geq \sigma_2 \geq \sigma_3 \cdots \geq \sigma_n$.

2. Determine k weakest components that need to be improved, and that can be done by finding the maximum value of i such that

$$\sigma_i > \frac{U_t - \sum_{i=i+1}^{n+1} \sigma_i}{i} = \psi_i \tag{4}$$

where $\sigma_{n+1} = 0$ and $U_t = 1/A^t - 1$

3. The allocated unavailability contributions are

$$\sigma_i^a = \begin{cases} \psi_i & i \le k \\ \sigma_i & i > k \end{cases} \tag{5}$$

4. Calculate the unavailability contribution reduction factor for component i, i.e., $\beta_i = \sigma_i^a / \sigma_i$.
5. Calculate the relative reliability and restoration time improvement costs as

$$r_{\lambda_i} = \frac{C_{\lambda_i}^2}{\left(C_{\lambda_i} + C_{M_i}\right)\sum_{i=1}^{k} C_{\lambda_i}}, \quad r_{M_i} = \frac{C_{M_i}^2}{\left(C_{\lambda_i} + C_{M_i}\right)\sum_{i=1}^{k} C_{M_i}} \tag{6}$$

6. Determine θ_i such that

$$\beta_i = \left(r_{\lambda_i} \cdot r_{M_i}\right)^{\theta_i} \Rightarrow \theta_i = \frac{\ln(\beta_i)}{\ln(r_{\lambda_i} r_{M_i})} \tag{7}$$

7. The allocated λ and M will then be

$$\lambda_i^a = r_{\lambda_i}^{\theta_i} \lambda_i, \qquad M_i^a = r_{M_i}^{\theta_i} M_i \tag{8}$$

and the rest $n-k$ remain unchanged.

As indicated in Fig. 6, there may be situations where there is no budget (or desire) for improvement for the failure rate *or* the restoration time of a component. In this case, the value of the associated relative cost r should be 1. The relative cost calculation for other components should not take this failure rate (or restoration time) into account. This can be done by setting the improvement cost of the reliability or restoration time equals to zero while calculating the relative costs for others, and then assign 1 as its value for r. Further, in situations where improvement is known to be impractical (or undesired) for *both* the failure rate and restoration time of a component, the following modification is necessary. Suppose no improvement is allowed for component l, the unavailability contribution reduction factors should be adjusted as

$$\beta_i^* = \frac{k \cdot \sigma_k^a - \sigma_l}{\sigma_i}, \quad i \ne l \tag{9}$$

B. Allocation procedure (complexity based)

If component improvement cost is difficult to estimate or allocating the availability target with minimum cost is of less relevance, it may be important instead to consider relative complexity. Jigar et al. [5] have proposed a calibration method that may replace component's improvement cost (C) by a complexity score (Z). The complexity score for component i measures how difficult it is to perform an improvement compared to other components. With this complexity-based allocation, the intention is to minimize the total improvement effort (or "complexity"). The steps presented in [5] are repeated below:

1. Apply steps 1 to 3 in Section A to identify the weakest components.
2. Determine, among the identified components, the most complex (difficult) failure rate or restoration time to improve. With respect to failure rate, the complexity may be the difficulty to increase the MTTF per hour and for restoration time to increase the restoration rate per hour.
3. Assign a maximum score (Z) associated with this failure rate or restoration time. The maximum score can be 10 or any other order. Note that the maximum score does not imply that improvement is not going to take place. If there is a desire however to not allow improvement, Z must be omitted or can be set to zero.
4. Assign scores for the remaining failure rates and restoration times relative to this maximum score.
5. Apply equation 6 to calculate the relative complexity factors for failure rates and restoration times. The same procedure as in Section A can then be applied to perform the allocation.

V. EVALUATION AND DECISION-MAKING

Decision-making is a process that could suffer from bias if two or more stakeholders present conflicting objectives. The trade-off is to choose among the many alternative availability improvement solutions [23]. The allocation method presented above may help to find a balanced solution given stakeholders' needs. The method allocates system availability target down to the level of component reliability and restoration time such that the total improvement effort (cost/complexity) is minimized. This is also to mean that a certain "amount" of performance improvement with the associated cost will be allocated to a stakeholder such that the required system performance is achieved with minimum total improvement cost. As clearly indicated in [8], decision-making is not a “once and done” event. The decision made at a certain step should be evaluated, communicated to relevant stakeholders and refined as design of the system progresses and more data become available.

As can be seen from the SPADE method, Fig 2, evaluation is located in the centre to convey continuous evaluation while the allocation process is evolving. Each task, namely stakeholder identification and recognition of their needs, problem formulation, alternative assessment and decision-making, needs to be continuously evaluated. According to Haskins (2008a: 28), “… continuous evaluation means being open to recognizing new stakeholders, allowing their late-arriving viewpoints to influence the framing of the problem and the list of alternative options. Decisions are evaluated based upon measures of performance and success criteria identified at the time of problem formulation.”

VI. CONCLUSION

Following a systems engineering framework, the paper proposes a new perspective to carry out availability allocation for complex systems. The paper uses the systems engineering SPADE method, and the benefit is that it helps to conduct availability improvement analysis in an iterative and systematic manner. The central idea of the method is to structure the availability allocation problem and assessment of the solution in such a way that stakeholders’ needs are met with the quality as specified in the measures of effectiveness (MOEs). Measures of effectiveness (MOEs) are performance criteria that are set in the problem formulation phase so that the availability improvement process strives towards finding a solution that satisfies that criterion. Continuous evaluation of the progress of the availability allocation process is also another core idea of the method.

The proposed perspective is a concept that has not been tested by using a realistic case study and it is our suggestion for further research work to implement it against a realistic case study. In addition, the only focus in this paper has been on production systems. However, system availability is a key measure for safety systems as well and consideration of the systems engineering perspective for such systems would also be of interest. Further, implementing effective modularization is a common and efficient measure to improve availability through reducing the restoration time. Modularization requires a holistic perspective since modularizing a certain subsystem affects the remaining subsystems. The proposed method can be further developed to take into account modularization issues in detail.

REFERECES

1. Rausand, M. and A. Høyland, *System reliability theory: models, statistical methods, and applications*. Vol. 396. 2004: John Wiley & Sons.
2. Elegbede, C. and K. Adjallah, *Availability allocation to repairable systems with genetic algorithms: a multi-objective formulation.* Reliability Engineering & System Safety, 2003. 82(3): p. 319-330.
3. Amari, S.V. and V. Hegde. *New allocation methods for repairable systems*. in *Reliability and Maintainability Symposium*. 2006. p. 290-295.

4. McNichols, R.J. and G.H. Messer Jr, *A cost-based availability allocation algorithm.* Reliability, IEEE Transactions on, 1971. 20(3): p. 178-182.
5. Jigar, A., M.A. Lundteigen, and Y. Liu, *A new availability allocation method*, in *ESREL*. 2015, Taylor & Francis Group, London: Zürich, Switzerland. p. 2197-2205.
6. Mitchell, R.K., B.R. Agle, and D.J. Wood, *Toward a theory of stakeholder identification and salience: Defining the principle of who and what really counts.* Academy of management review, 1997. 22(4): p. 853-886.
7. Kuo, W. and R. Wan, *Recent advances in optimal reliability allocation*, in *Computational Intelligence in Reliability Engineering*. 2007, Springer. p. 1-36.
8. Haskins, C., *Systems engineering analyzed, synthesized, and applied to sustainable industrial park development*. 2008, Norwegian University of Science and Technology.
9. Fraser, J. and A. Gosavi. *What is systems engineering?* in *American Society for Engineering Education*. 2010.
10. INCOSE. cited November 30, 2015; Available from: http://www.incose.org/AboutSE/WhatIsSE.
11. Bahill, A.T. and B. Gissing, *Re-evaluating systems engineering concepts using systems thinking.* Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on, 1998. 28(4): p. 516-527.
12. Bahill, A.T. and F.F. Dean. *What is systems engineering? A consensus of senior systems engineers*. in *INCOSE 6th Annual Int Symp*. 1996: p. 503-508.
13. Haskins, C., *Using systems engineering to address socio-technical global challenges.* Proceedings CSER08, 2008.
14. Liu, Y. and M. Rausand, *Reliability effects of test strategies on safety-instrumented systems in different demand modes.* Reliability Engineering & System Safety, 2013. 119: p. 235-243.
15. Lundteigen, M.A. and M. Rausand, *Reliability of safety instrumented systems: Where to direct future research?* Process safety progress, 2010. 29(4): p. 372-379.
16. Rausand, M., *Reliability of Safety-Critical Systems: Theory and Applications*. 2014: John Wiley & Sons.
17. Shainee, M., et al., *Designing offshore fish cages using systems engineering principles.* Systems Engineering, 2012. 15(4): p. 396-406.
18. Fet, A.M., *Systems engineering methods and environmental life cycle performance within ship industry.* Doktor Ingeniøravhandling, 1997.
19. Clarkson, M.E., *A stakeholder framework for analyzing and evaluating corporate social performance.* Academy of management review, 1995. 20(1): p. 92-117.
20. Murthy, D., T. Østerås, and M. Rausand, *Component reliability specification.* Reliability Engineering & System Safety, 2009. 94(10): p. 1609-1617.
21. Tsai, Y.-T., K.-S. Wang, and L.-C. Tsai, *A study of availability-centered preventive maintenance for multi-component systems.* Reliability Engineering & System Safety, 2004. 84(3): p. 261-270.
22. Sproles, N., Formulating measures of effectiveness. Systems Engineering, 2002. 5(4): p. 253-263.
23. Oliver, D.W., T.P. Kelliher, and J.G. Keegan Jr, *Engineering Complex Systems*. McGraw-Hill Companies , 1997.

BIOGRAPHY

Abraham Almaw Jigar is a PhD candidate in the department of production and quality engineering at the NTNU. His main research topic is reliability assessment of safety-critical systems. He earned BSc. in statistics from the university of Gondar, Ethiopia, and masters in mathematics from NTNU. Abraham has worked as a reliability engineer at Aker Solutions, Norway, for one year before he started his PhD.

Cecilia Haskins is an Associate Professor in systems engineering at NTNU. Her educational background includes a BSc in Chemistry from Chestnut Hill College, and an MBA from Wharton, University of Pennsylvania. She has been recognized as a Certified Systems Engineering Professional since 2004. After earning her Phd from NTNU, she teaches and conducts research on innovative applications of systems engineering to socio-technical problems such as those encountered in sustainable manufacturing and global production systems.

Mary Ann Lundteigen is a professor in reliability assessment at NTNU with the main research focus on reliability assessment of safety-critical systems. She has a combined academic and industrial background, primarily related to the oil and gas industry. She has a MSc. in engineering cybernetics and a PhD in RAMS (reliability, availability, maintenance, and safety). Currently, she is heading the RAMS group at NTNU, and she is also the co-director of the new Norwegian Center of Excellence for subsea production and processing (SFI SUBPRO). Since 2006, she has also been a member of the technical committee for updating IEC 61511, a key standard that frames the design and operation of safety-instrumented systems for the process industry.