RISK ASSESSMENT OF SYSTEMS DURING DEVELOPMENT PHASE: AN APPROACH BASED ON LIFETIME FUNCTIONS

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Abstract. Quantifying the time-dependent risk associated with complex engineering projects is an essential task to ensure the success of these projects. Low technology readiness and maturity levels and uncertainties associated with different development scenarios and management decisions are among the risk mechanisms which may affect a system. Accordingly, monitoring the risk associated with a project during its development phase is necessary in order to achieve satisfactory outcomes. This paper investigates the applicability of system reliability concepts in assessing the risk associated with engineering systems during their development phase. A system-based approach to quantify risk associated with a systems, based on time-dependent system reliability principles applied through lifetime functions, is proposed. The approach starts with defining the probabilistic parameters associated with the development time of each component in the system. A measure of time-dependent system performance is established next and combined with the project consequences to compute the time-dependent system risk. In the presence of multiple scenarios associated with system development, risk profiles of each scenario are identified and compared. Moreover, a bi-objective optimization problem is formulated and solved to obtain the development scenarios which provide the lowest risk while minimizing the system development cost.

Key words: risk assessment, lifetime function, optimization.

1. INTRODUCTION

Monitoring the risk associated with engineering projects during the development phase is necessary to ensure the success of these projects. In this phase, risks may occur due to low technology readiness and maturity levels and uncertainties associated with different development scenarios and management decisions, among others [1, 2]. Technology readiness levels (TRLs) have been used by the National Aeronautics and Space Administration (NASA), United States Department of Defense (USDOD), and Department of Energy (USDOE) [3, 4], among others, to assess the maturity and readiness of engineering projects. Additionally, attempts to apply the approach for a wide range of engineering problems such as manufacturing [5, 6], aerospace

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Ro. J. Techn. Sci. – Appl. Mechanics, Vol. 62, N° 1, P. 7–17, Bucharest, 2017

design [7], and software development [8, 9] have been made. The technology readiness metric adopted by NASA defines nine possible TRLs for a given technology and it determines the risk associated with insertion of a new technology into a mission or mission element [10]. Although this approach is widely adopted by several agencies, the TRL scale is not linear or proportionate; accordingly, quantitative analysis on a system level integrating the TRL of individual components is not possible. Therefore, quantitative probabilistic risk analysis cannot be based solely on the TRL assessment of the components within an engineering system. As a result, approaches relying on detailed decision tree models for identifying risk associated with specific project scenarios have been proposed [2]. However, there is a lack in approaches which provide in-depth time-dependent analysis suitable for quantitatively assessing the risk associated with technological projects during their development phase [11].

This paper presents a tool for assessing the time-dependent risk associated with engineering systems during their development period. A probabilistic method is proposed to assess the risk associated with the development and maturity time. Moreover, based on system reliability analysis, risk associated with projects due to development delays, or lack of readiness, of the system components is quantified. In the presence of multiple development paths or scenarios, each having its own cost and development time, it is necessary to find the optimum development path or scenario which minimizes the development costs simultaneously with minimizing the risk associated with the project. Accordingly, a bi-objective optimization problem is constructed and solved to obtain the optimum development paths which minimize the total project cost and the risk associated with the project. Finally, updating the risk profiles in light of new data collected during the development process is also investigated.

2. SYSTEM PERFORMANCE

Lifetime functions offer multiple indicators that are widely used for assessing the performance of components and systems in several engineering disciplines [12]. Specifically, these indicators have been used for assessing the performance of civil structures, such as bridges, under gradual deterioration [13]. Several lifetime functions can be defined for a typical system with deteriorating components, including the probability density function (PDF) of the time to failure, cumulative-time probability of failure, survivor function, hazard function, and cumulative hazard function. Each of these functions represents a distinctive feature of the system that may be useful for assessing the performance of the system during its service life.

Using the same concepts developed for deteriorating structures, the performance of the system during its development phase can be assessed by using lifetime functions. In such case, the PDF of development time should be first identified. Next, the cumulative-time probability of component development can be found as will be shown later. Moreover, the probability that the system will not be developed, or ready, at a certain time can also be obtained. By integrating the consequences of lack of readiness, a measure of risk associated with the system can be established.

2.1. PDF of Development Time

The PDF of development time *D* can be defined analogously to the definition of the random time to failure *T* of a structural component. *T* is defined as the time elapsing from placing the component into operation until it fails for the first time [14]. Accordingly, *D* is defined as the time elapsed from starting the development process of a component up to the end of this process when it is ready to be integrated into a system. The PDF of the development time can be found through the statistical information of the development or manufacturing process. Identifying the PDF of *D* is the first step to calculate the rest of the system performance measures. For a small time interval Δt and a given time *t*, this PDF provides the probability that the system will be developed and ready for deployment between the time *t* and $(t+\Delta t)$. Therefore, it has the following probabilistic interpretation

$$f_D(t)\Delta t = P\left(t \le D \le \left(t+\Delta t\right)\right), \tag{1}$$

where $P(\cdot)$ represents the probability of occurrence of the event between parentheses.

2.2. Cumulative-time Development Probability

If the PDF of the development time of a component is known, the cumulative probability $F_D(t)$, representing the probability that component has been developed before time *t*, can be obtained as

$$F_D(t) = P(D \le t) = \int_0^t f(x)\mathrm{d}x. \tag{2}$$

Additionally, the cumulative probability that the component has not been developed, or not ready, at time *t*, $\bar{F}_D(t)$, can be expressed as

$$\bar{F}_D(t) = 1 - F_D(t) = P(D > t) = \int_t^\infty f(x)\mathrm{d}x. \tag{3}$$

In the presence of time constraints associated with the system development, this cumulative probability can be used to assess the risk associated with an engineering project due to lack of readiness at a required time.

Consider a system composed of several components that should be fully developed in order for the system to function properly. Based on this condition, the system can be modeled as a series system of these interconnected components.

Assuming statistical independence between the development events of the components, the cumulative probability $F_D^{sys}(t)$, representing the probability that the system has been developed at time t is expressed as

$$F_D^{sys}(t) = \prod_{i=1}^{n} F_D^i(t), \tag{4}$$

where $F_D^i(t)$ is the cumulative probability of development of the i-th component at time t and n is the number of components. System probabilities for other system configurations, such as parallel or series-parallel systems, can also be formulated [12]. Accordingly, if the consequences $C(t)$ associated with the undeveloped system at time t are known, the cumulative-time system risk can be computed as

$$R^{sys}(t) = \bar{F}_D^{sys}(t) \cdot C(t). \tag{5}$$

3. ILLUSTRATIVE EXAMPLE

Consider a system with four components that must be fully ready and mature in order for the system to be fully functional. Since the system cannot function with any undeveloped (or not ready) component, the system in this format can be modeled as the series system of connected components shown in the upper left insert in Fig. 1. Assuming that the development time of the components follows a Weibull distribution with the mean value and standard deviation for each of the components shown in Fig. 1, the probability density function of the development time for each of the components can be plotted as shown in Fig. 1.

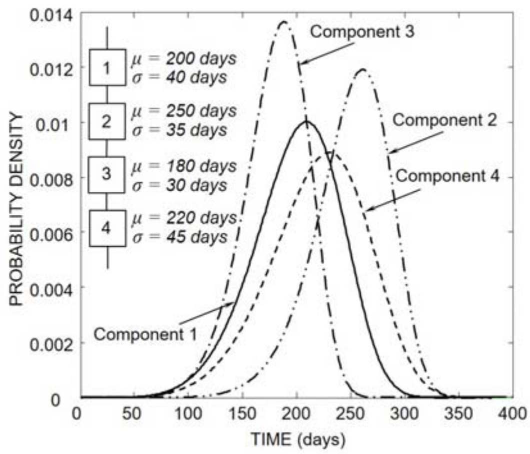

Fig. 1 – Probability density function and probabilistic descriptors of the development time associated with the four components of the system.

The cumulative probability that the system has been developed at time *t* can be found using Equation (4). This probability is depicted in Fig. 2 for the individual components and the series system of interconnected components, assuming that the development events of the individual components are statistically independent.

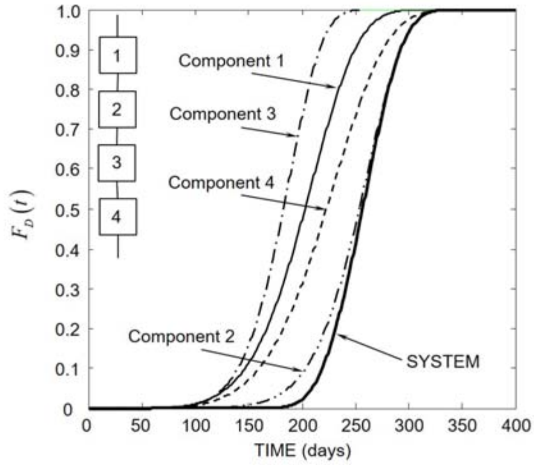

Fig. 2 – Cumulative-time probability associated with the development time of the components and the system.

The probabilities that the components and the system have not been developed at time *t* are plotted in Fig. 3. The risk arising from the system being undeveloped at a given point in time can be evaluated based on the cumulative-time system probability $\bar{F}_D^{sys}$ plotted in Fig. 3.

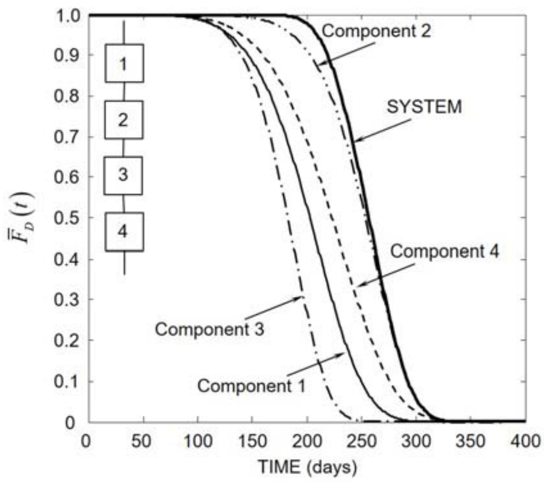

Fig. 3 – Complement of the cumulative-time probability associated with the development time of the components and the system.

For computing the risk, the loss arising from the system being undeveloped (i.e., not ready or not mature) at a given time should be integrated with the probability $\bar{F}_D^{sys}$. In this example, it is assumed that a loss will occur if the system is not fully developed in 250 days. Additionally, a penalty is added for each extra day with an unready system. Accordingly, the loss function is assumed as

$$C(t)=\begin{cases} 0 & \text{for } t \le 250 \text{ days} \\ 10+\exp\left(\lambda\cdot(t-250)\right) & \text{for } t > 250 \text{ days} \end{cases}. \tag{6}$$

Figure 4 shows the risk profiles associated with the system not being ready at 250 days or greater for three values of parameter λ (i.e., 0.10, 0.11, and 0.12). Needless to say, any other time-based loss function can be used within this approach.

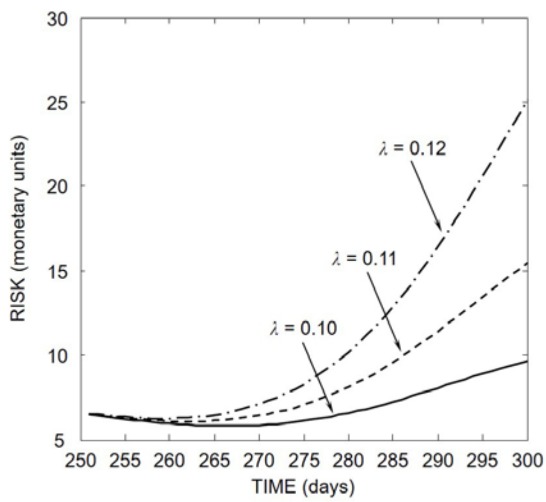

Fig. 4 – Risk associated with the system development for three values of the parameter λ.

Risk should also be monitored during the development of system components. For instance, if at time $t = t_0$ the system has been assessed and all the components were found to be still under development, then the PDF of the future development time can be computed in light of this new information. Hence, given that the components have not been ready at time t_0, the probability that a component will be developed at or before time $t + t_0$ is

$$P\left(D \le t+t_0 \mid D > t_0\right)=\frac{F_D\left(t+t_0\right)-F_D\left(t_0\right)}{\bar{F}_D\left(t_0\right)}. \tag{7}$$

Accordingly, the PDF of the future development time is $\dfrac{f_D\left(t+t_0\right)}{\bar{F}_D\left(t_0\right)}$.

Figure 5 shows the PDF of future development time assuming that the components have not been ready at time $t_0 = 200$ days. In such case, a future updated risk profile can also be obtained given the new information. The original and updated risk profiles for $\lambda = 0.12$ are shown in Fig. 6. Since the components have not been developed until 200 days, the risk associated with the system development will increase in the manner indicated in Fig. 6.

This formulation provides the time-dependent risk associated with a given system developed with a certain scenario. However, for engineering systems, multiple development scenarios or paths for each component of the system may exist. Accordingly, the expected risk profile will change depending on the development path and each solution will have its own risk with an associated development cost.

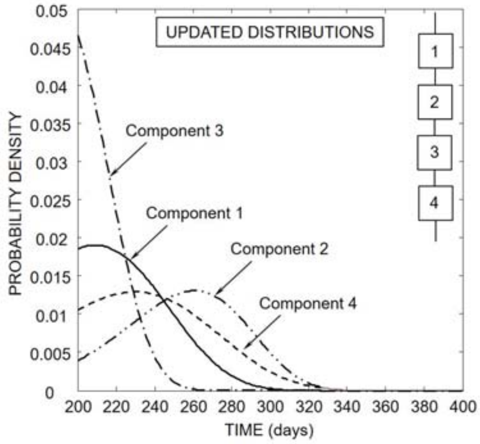

Fig. 5 – Updated probability density functions of future development time assuming that the components have not been ready at time $t_0 = 200$ days.

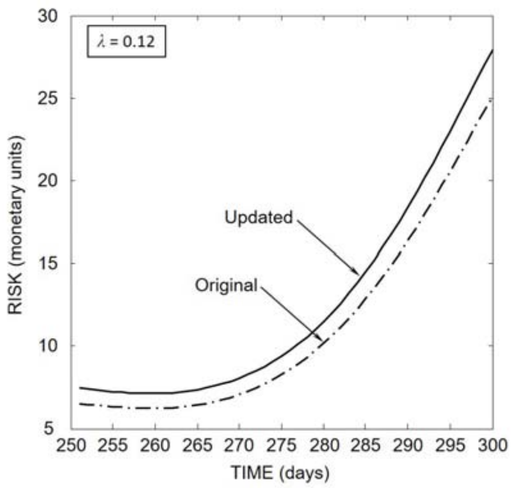

Fig. 6 – Original and updated risk profiles for $\lambda = 0.12$ assuming that the components have not been ready at time $t_0 = 200$ days.

Since scenarios with lower risk may be associated with higher development costs, multi-criteria optimization should be used to obtain the optimal tradeoffs between these two conflicting objectives. In this example, multi-criteria optimization using genetic algorithms (GAs) is performed next to illustrate this optimization process.

Consider the same system of series components discussed above, where in this case, each component can be developed by one of three methods, namely A, B, or C. Each method is associated with certain descriptors of development time and development cost. The mean value, standard deviation, and cost associated with each development method for each component are shown in Table 1.

Table 1

Details of different development options associated with the optimization problem

Component	Method	Development Time		Development Cost (monetary units)
		Mean (days)	Standard Deviation (days)	
Component 1	A	180	30	15
	B	160	28	18
	C	120	20	25
Component 2	A	160	50	6
	B	140	40	10
	C	130	40	15
Component 3	A	240	60	25
	B	200	35	28
	C	180	30	30
Component 4	A	90	15	10
	B	80	15	15
	C	72	12	20

Based on this information, a multi-criteria optimization problem can be formulated as follows

$$\text{Find: } \mathbf{I} = \{i_1, i_2, i_3, \ldots\ldots.., i_n\}. \tag{8}$$

$$\begin{gathered}\text{To minimize: (a) maximum time-dependent system risk } R^{sys}(t) \\ \text{and (b) total development cost } C_{total}\end{gathered} \tag{9}$$

$$\text{Given: } \boldsymbol{\mu}, \boldsymbol{\sigma}, C(t), \text{ and } \mathbf{C}, \tag{10}$$

where **I** is a vector consisting of the method identifier i_k associated with the k-th component in the system and n is the number of components (i.e., four in this case). For this example, since each component has three development options, the identifier i_k can take the value of 1, 2 or 3 for each component, corresponding to the options A, B, and C respectively. $R^{sys}(t)$ is the time-dependent system risk, and C_{total} is the total development cost obtained as the summation of development costs of each component. **μ** and **σ** are vectors consisting of the mean values, and standard deviations, respectively, associated with different development methods for each component. **C** is a vector consisting of the development cost associated with the different development methods of each component, which is treated deterministically in this example.

The optimization problem is formulated in MATLAB® environment and solved by using the multi-objective generic algorithm solver in the Global Optimization Toolbox® version 3.2.4 [15] which employs a variant of the non-dominated sorting genetic algorithm with controlled elitisms (NSGA-II) [16]. The results of the optimization problem are shown in Fig. 7.

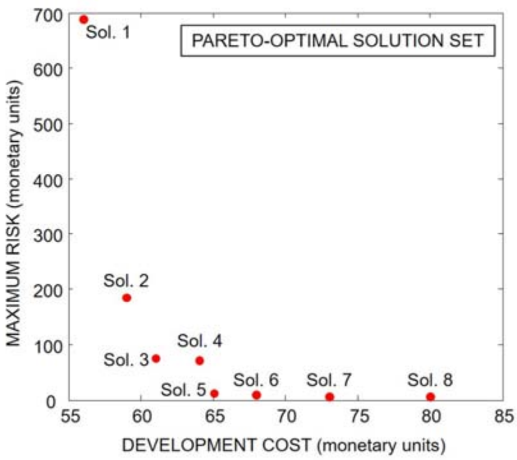

Fig. 7 – Pareto-optimal solution set of the bi-objective optimization problem minimizing both maximum system risk and the total development cost.

Among all the possible combinations, eight solutions were found to belong to the Pareto-optimal solution set. A solution is Pareto-optimal if there doesn't exist another solution that improves at least one objective without worsening another one [17]. The details of each solution are shown in Table 2. The letter sequence of various solutions indicates the optimum development method for each of the four components. For example, Solution 1 specifies B-B-C-A as the optimum development path. This means that the first to fourth components should be developed by using method B, B, C, and A, respectively. As can be seen, the two objectives (i.e., minimizing maximum risk and development cost) are conflicting and the optimum tradeoff can be found through the solution of the optimization problem. Solutions characterized by low development cost (such as Solutions 1 and 2) are also characterized by higher maximum risk values compared to other solutions on the front. Solutions 3 and 4 have very close maximum risk values but different development times. Finally, Solutions 5 through 8 have low risk values compared to the first four solutions but they vary in the cost value. By setting thresholds on the development cost and maximum accepted risk, the optimum development plan can be obtained.

Table 2

Details of optimum solutions
in the Pareto-optimal solution set

Solution	Risk (monetary units)	Development Cost (monetary units)	Development Scenario
1	691.15	56	B-B-C-A*
2	183.49	59	A-A-B-A
3	73.43	61	A-A-C-A
4	69.86	64	B-A-C-A
5	10.30	65	A-B-C-A
6	6.53	68	B-B-C-A
7	5.17	73	B-C-C-A
8	5.15	80	C-C-C-A

*From left to right, letters indicate the optimum development method for components one to four, respectively.

4. CONCLUSIONS

This paper presented a probabilistic method for assessing the time-dependent risk associated with the development phase of engineering systems. Based on the probability density function of the development time, risk associated with the system due to development delays, or lack of readiness, of different components was quantified. Updating the risk profiles in light of new data collected during the development process was also investigated and the change in risk profile was quantified. Moreover, a bi-objective optimization process was constructed and solved by using GAs to find the optimum development path or scenario which minimizes the development costs simultaneously with minimizing the maximum risk associated with the project. This is a crucial task when multiple development paths or scenarios, each having its own cost and development time, exist.

Based on the probability density function of the development time of each component, the cumulative-time probability that the system will not be ready at a given time was obtained. This probability was next integrated with the consequences of this event to obtain a measure of the risk associated with the system. The proposed approach can be effectively used to assess the risk associated with engineering projects during the development phase. However, more research is still needed to better quantify the interactions and correlations between various components within a system.

Acknowledgements. The authors gratefully acknowledge the financial support of the Pennsylvania Infrastructure Technology Alliance (PITA) through contract 543031 “PITA XVI: Reliability, Maturity and Readiness of Complex Systems”. The authors sincerely thank Lockheed Martin for their support. The opinions and conclusions presented in this paper are those of the authors and do not necessarily reflect the views of the sponsoring organization.

Received on February 2, 2017

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