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Towards the Design of Resilient Large-Scale Engineering Systems

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Abstract

Resilience has mostly been thought of as the ability to recover from adversity. However, it is now increasingly recognised that resilience should not only serve as a means for organisations to survive hardship, but also to thrive and prosper. For large-scale engineering systems, such as telecommunications networks and power grids, this is vital due to relatively long life cycles leading to large uncertainties, and also due to the significant investments involved. Exactly how this and thus resilience should be designed into such systems, however, is less well defined. Here, the term resilience is explored through engineering, organisational and ecological literature to understand differing perspectives from select domains before distilling these into the three engineering design lifecycle properties: robustness, adaptability and flexibility. In particular, a distinction is highlighted between adaptability and flexibility following findings in literature. These properties and the concept of resilience are discussed with reference to system performance in order to serve as requirements for designing large-scale resilient engineering systems.

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Keywords: Resilience; engineering systems; engineering design

1. Introduction

Resilience has traditionally been associated with negative connotations: the ability to recover from adversity or trauma. Indeed, a basic definition from the Oxford English Dictionary [1] gives: "The quality or fact of being able to recover quickly or easily from, or resist being affected by, a misfortune, shock, illness, etc.; robustness; adaptability". While this similar in other dictionaries [2,3], there is less consensus across domains in academia and in industry.

The term "resilience" was first popularised by Holling within the field of ecology to assess the stability and resilience of interacting populations and the environment [4]. In their work, the term is defined as the "persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist". This concept of a system's interaction with the environment and surviving disturbances is similar to the foundations for resilience in many other fields including supply chain management [5], crisis management [6], psychology [7] and resilience engineering [8]. However, there is now growing recognition that resilience not just allows for recovery, but also to allows for the ability to thrive and prosper following difficult times [9].

This is especially relevant for large-scale engineering systems, such as communication networks and energy production plants, which have relatively long life cycles, typically 10 or more years, and incur significant investments. As a result of such long time scales, such systems not only need to withstand imminent shocks but also have to be designed such that it can cope with and build upon evolving technologies into the future. It is thus argued here, that by designing large-scale engineering systems to be resilient, they are better equipped to weather hardship and also succeed in the future.

Exactly, how resilience is designed into engineering systems, however, is less well established. To better understand how resilience may be incorporated for large-scale engineering systems, this paper first examines literature from engineering, management and ecology to understand different views of resilience. These fields are specifically included since contrasting insights were found. Following this, these

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views were then related to engineering design concepts to form requirements for the design of resilient engineering systems and discussed for applications to a large-scale engineering systems.

2. Views of Resilience

Resilience has demonstrated applicability to many domains. Through exploration of the resilience literature, it was found that a system must be designed to withstand disturbances, yet also continue to perform well as the environment changes. Further examination of the resilience literature suggests that this may be achieved through three characteristics: absorbing disturbances, adapting for change and thriving for the future.

2.1. Absorbing Disturbances

Traditionally in engineering and most domains, resilience has been typically thought of as a recovery from some disturbance. This can be achieved through simply having enough resources or redundancy to absorb shocks. For example, a bridge may be built to have sufficient structural strength to withstand all foreseen loads.

This view of resilience stems from early work in designing High Reliability Organisations which focused much more on risk and safety management in engineering [10]. Early case studies involving resilience thus focus on high risk industries such as nuclear plants [11], offshore helicopter transport [12], and the Columbia Space Shuttle disaster [13]. As such, much of this analysis revolves around analysing vulnerabilities, risk analysis and calculating the probability of failure in engineering systems so that the system performs as expected in operation.

These ideas evolved to recognize that it is impossible to conceptualise every failure in the system and that it is better to enable the system to respond appropriately to disturbances when they do occur [14]. This view of resilience is therefore achieved by designing the system to be robust so that it simply absorbs all disturbances within some margin and continues to perform, giving some desired output. Such behaviour may be achieved through buffering capacity [15], redundancy [16] or by including tolerance into the system [17].

The key idea amongst these terms is that the system is able to maintain performance without the need to change the system if the disturbance is within a certain margin.

2.2. Adapting for Change

Absorbing disturbances alone is not sufficient for resilience, however, and the key factor that separates resilience from other system properties such as "brittleness" or "vulnerability" is the need for adaptive capacity in the system to continue normal operations [14;18]. In this sense, a recovery requires actual change in the system to maintain a desired output. This could be a reorganization of resources, as typically seen in management and organizational literature, or control systems where feedback loops maintain a desired output.

This is typically employed where the margins are too large or impractical to be "absorbed". That is, the range of disturbances may be sufficiently large such that one robust design may not be enough or practical to maintain system performance. Studies with this view of resilience include how communities handled the aftermath of Hurricane Katrina [19] and the terrorist attacks of 9/11 [20]. In both cases, it was found that having a contingency plan was a clear benefit and helped to save lives. However, another study further investigated the effect of the destruction of the Emergency Operations Centre during the 9/11 attack which disrupted planned protocols. It was found that key to maintaining operations was integrating the adaptive capacity of the response organization with the resources of New York City, private entities, and government at all levels. These examples highlight the need to be prepared for eventualities in order to "absorb" disturbances through contingency plans, but also demonstrate that the ability to adapt, when there is no clear plan, is necessary to achieve resilience. Dalzielle and McManus [16] captures this by defining resilience as a combination of having "enough redundancy to provide continuity of function, or through increasing the ability and speed of the system to evolve and adapt to new situations as they arise". As such, resilience, in these domains is measured by the recovery time to return to a previously undisturbed state [21;22].

The key idea of adaptation in this sense is that the system is able to maintain performance with some internal change to the system.

2.3. Thriving for the Future

While the ability to adapt is essential for resilience, adaptation takes a slightly different, yet significant, view in the field of ecology. From an ecological resilience perspective, adaptation refers to a system moving between states of equilibria [23]. Ecology focuses on the interactions of a systems, be it organisms or natural systems such as lakes, and the environment. Such work concentrates on maintaining equilibrium in systems and a disturbance may, for example, cause a fluctuation in population numbers of interacting species. If there is a significant disturbance, an introduction of a species say, the system of species will fall into a different set of equilibria or states which may lead to the extinction of a species. Therefore, adaptation in the ecological sense refers to a system moving between system states and resilience is defined as the "ability to absorb change and disturbance and still maintain the same relationships between populations or state variable" [4]. With such a definition, resilience in ecology is measured by the amount of disturbance the system can take until the system changes to another equilibrium or state [24;25].

This notion of changing or evolving the system between states in resilience has carried over to other domains and it is now recognised that in order to achieve resilience, the system should also "thrive" by adapting for opportunities for better performance [9]. Adaptation in this context thus involves changing the system performance, not back to normal in the previous case, but to a better performance level or another equilibria. Furthermore, with this concept of changing system states, there has also been a change in sentiment: Resilience has traditionally been thought of as a response to adversity, but now it includes a more positive view where it serves to grow a system for new opportunities.

The key to this view of resilience is that the system no longer reverts back to a defined system performance, but instead, through some change of the system, alters its performance following new opportunities.

3. Designing for Resilience

Having found the characteristics of resilience in relevant literature, these concepts are now explored in the context of engineering design. The three characteristics of absorbing disturbances, adapting for change and thriving for the future are seen to correspond to the system lifecycle properties robustness, adaptability and flexibility respectively. It should be noted, however, that there is significant overlap in the definitions of adaptability and flexibility in literature. Here, these subtleties are defined to give requirements for future design of engineering systems.

3.1. Robustness

Through examining the literature, redundancy, tolerance and margins were identified as factors through which to achieve resilience. In engineering design, these methods are associated with robustness.

Robustness gained attention through Taguchi's [26] seminal work in controlling quality in product manufacture. Variations in quality were attributed to noise factors and hence robustness is where “the product’s functional characteristic is not sensitive to variations in the noise factors”. In Taguchi's work, robustness is applied by reducing deviation from a target value and was realised through system design, parameter design and tolerance design.

Formally, robustness may be defined as the ability to be “insensitive towards changing environments” [27]. In essence, the system does not respond to variances in the environment nor changes any processes or properties when faced with disturbances, yet maintains required a desired output. For example, a bridge may be designed to be robust to withstand extra loading from increased traffic or wind. This design may be more cost efficient when the margins and disturbances are predictable, but may fail if there are unexpected influences on the system which push the system beyond the designed tolerances. For this reason, robustness may suit designs for the near future where uncertainties are relatively more understood or where the demands on the system is unlikely to change throughout the system lifecycle. This, however, means that robustness is not sufficient for resilience since the future, especially for complex engineering systems, can be uncertain and demands may change.

3.2. Adaptability

The ability to adapt has also been identified as being essential to resilience. There is, however, a lack of consensus concerning the definitions of “adaptability” and “flexibility” in engineering design literature and the terms are often used synonymously. Here, adaptability is used to denote where the system can change through an internal change agent [27;28] and is similar to the concept of “adapting for change” as defined in the previous section. An internal change agent suggests that change is initiated within the system. This is opposed to an external change agent where an external decision maker prompts change to the requirements of the system. Specifically, the internal change agent serves to recover the system to a predefined or previous state to maintain acceptable performance without the need for external actuation. For example, with this definition for adaptability, the Design for Adaptability proposes a framework where control and feedback are used to modify system performance [29]. In this case, adaptability could involve changing inputs through control algorithms such as look-up tables or standard linear control algorithms to maintain some desired state. Another example could be an aircraft which maintains stability and adapt to changes in flight conditions through a lookup table of stability derivatives [30]. In this case, actuator positions are automatically adjusted as a function of flight conditions. These responses are also useful in high-risk situations where immediate responses are needed instead of waiting for human intervention [31].

An adaptable design may suit situations where it is impractical to make the system excessively robust. That is, it is not cost efficient or possible to have too much redundancy in the system. Instead, the system is designed to undergo known, foreseen changes to maintain performance. For this reason, adaptable design may be useful where uncertainties are relatively more understood in the near future or where the demands on the system is unlikely to change throughout the lifecycle.

3.3. Flexibility

From ecological literature, it was found that resilience required a system to adapt to new system states. This parallels with the idea that an engineering system can be changed to adapt for new opportunities and give different performances. This contrasts with robustness and adaptability which both serve to return a system back to normal operations.

In engineering design literature, flexibility is often used synonymously to adaptability and both are used broadly to refer to some change of the system. Here, the terms are differentiated through the location of the change agent. However, difficulties do arise depending on the definition of the location of the system boundary. For an adaptable solution, the change agent is internal to the system whereas for a flexible system, the change agent is external to the system. A flexible system therefore allows a decision maker to change the requirements and performance of the system [27]. The degree of flexibility may be assessed by the ability of the system to be changed easily. That is, a system may be designed so it can have a number of choices for a decision maker and a flexibility makes it is easy to change between the options. As such, flexibility may be achieved through modularity, platform design and interface design. Flexible designs thus enable a system to be modified to reach different requirements and, likening to concepts from ecological literature, achieve different states. By enabling the system to be changed for different requirements, it allows a system to evolve and potentially thrive when faced with substantial changes in demand.

Examples of flexible design include the Ponte 25 de Abril suspension bridge over the Tagus River in Lisbon, Portugal. Originally built with a single deck for road traffic, it was designed so that it had the strength to accommodate a secondary railroad deck in the future. Although adding a second deck involved a substantial retrofit, the planners or decision makers only exercised this option when there was enough demand stimulated by the single deck bridge [32;33] Essentially, the designers anticipated that the capacity of the bridge could grow which led to mechanisms being designed into the bridge at the conceptual stage so that capacity could be expanded when appropriate.

Flexible designs are especially important where the requirements could change in future. For large-scale engineering systems which typically lasts more than 10 years, it is likely that there are changes to demand and requirements. As such, flexibility may be employed for an engineering system which faces high uncertainty and where it is impractical to use an excessively robust design.

3.4. Relationship of Properties

In summary, robustness maintains desirable output or performance through designed margins, adaptability involves internal change to maintain a predefined performance and flexibility allows decision makers to change the system so that it can perform for new requirements. This is illustrated in Figure 1.

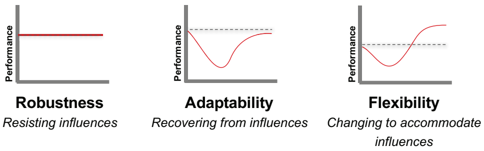

Fig. 1. Comparison of Robustness, Adaptability and Flexibility

Figure 1 shows how the system may respond to disturbances through robustness, adaptability and flexibility with respect to system performance. This is similar in ecology where Folke et al. [34] defines resilience as requiring three aspects: persistence, adaptability and transformability. Persistence is the ability of the system to remain in its original system state and corresponds to the concept of robustness. Adaptability is the ability of the system to adjust its processes for development within the current stability domain and relates to the concept of returning the system to a predefined state as per the definition of adaptability in the previous section. Transformability, on the other hand, is where the system "creates new stability domains for development" and parallels the idea of moving the system to another, better state.

With such definitions, it is apparent that each lifecycle property accommodates differing amounts of uncertainty. A robust system can only operate and handle a margin of uncertainty that was designed into the system at the conceptual stage. Once the system is deployed, these margins cannot be changed without replacing the system. For the example of a bridge, once the loading exceeds the designed limits, it will fail unless the bridge is replaced. Adaptability is similar in that the design also only tolerates uncertainty margins that were designed into the system at the conceptual stage. Although the system can change and adapt, there are bounds outside which the system will fail. For an aircraft, the control surfaces can change the position of its control surfaces, but again, once the disturbance is greater than the designed limits, it will also fail.

For both properties, the uncertainty margins have to be understood during conceptual design so that the system operates within these bounds once deployed. This initial understanding of the uncertainty margins at the conceptual design stage is termed here, the "initial robust bound" and shows the performance envelope of the system. This is illustrated in Figure 2.

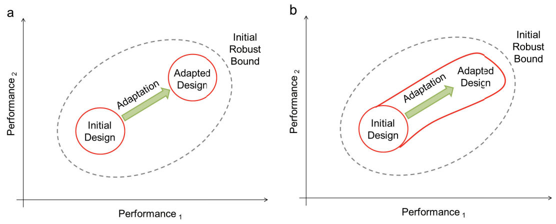

Fig. 2. (a) Performance boundaries of robustness and adaptability with separate performance envelopes. (b) Performance boundaries of robustness and adaptability with performance envelopes in union.

This shows an initial design with some robust performance boundary illustrated by a red circle. Through adaptation, an adapted design is reached which has another robust boundary and may have a performance boundary that is separate (Fig. 2.a) or in union (Fig. 2.b) with the initial design boundary. Although there is change, there is no need for external actuation and thus all adaptable designs must be foreseen at the time of design within the initial robust bound. There may be several adapted designs, which have not been shown for clarity, and the union of all robust boundaries at the point of deployment form an initial robust boundary. This initial robust boundary also gives the performance margin at the point of deployment and thus may be thought of the "total" robustness of the system.

Flexibility, on the other hand, allows for the system to operate in conditions that were not designed for in the initial design. It may be pre-empted that the requirements and thus the performance envelope may be subject to change, but the initial design would not be able to accommodate these new requirements. Therefore, flexibility is needed once the system is deployed and has to operate outside this initial robust boundary. This is shown in Figure 3.

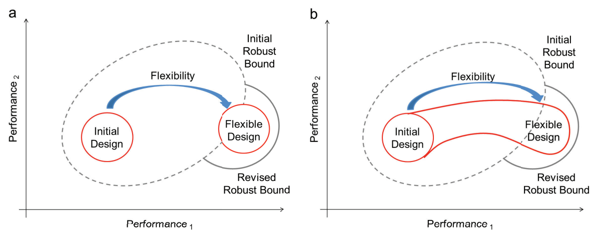

Fig. 3. (a) Performance boundaries of flexibility with separate performance envelopes. (b) Performance boundaries of flexibility with performance envelopes in union.

The initial robust bound, as before, represents the performance bound for robustness and adaptability when the system is deployed. Flexibility serves to modify this initial robust bound in some way and by doing so, creates a revised robust bound. As before, this new performance boundary may be separate (Fig. 3.a) or in union (Fig. 3.b) with the initial design. Flexibility therefore aims for the further future where uncertainties and required performance may be partially or completely unknown.

The previous discussion relates the three properties through uncertainty and performance. However, it is also important to note that these properties are related through time scales as well. Robustness and adaptability is applicable at all time scales, operational, tactical and strategic, provided the range of operations can be forecast to ensure the system can handle the range of predicted conditions. Flexibility is more involved with the strategic aims of a system where decision makers are given the choice of changing the requirements and performance of the system in the unforeseen future [33]. This is particularly important for resilience since the system has to be designed to withstand uncertainties that are predicted in the near future, yet also evolve for any opportunities that may arise. The evolution of the system properties can then be illustrated by Figure 4.

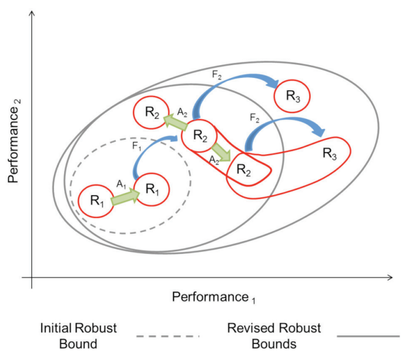

Fig. 4. Evolution of System Properties

The figure shows how a system can continue evolving through transitioning between uncertainty bounds. R_x and A_x represents robustness and adaptability respectively with the subscript indicating the robust bound of the design. F_x represents flexibility and the subscript indicates the transition between the bounds to evolve through time.

4. Resilience in Large-Scale Engineering Systems

For large-scale engineering systems, selecting the appropriate designs and transition paths incur significant investment since, unlike most products, they have relatively long lifecycles and it is difficult to replace the whole system for every opportunity. As discussed before, a robust system may be designed where uncertainties are predictable for whole system lifecycle. This could lead to savings compared to flexible designs. However, for large-scale engineering systems, the future is often uncertain and thus it is difficult to predict the requirements of the system for a substantial timeframe. Furthermore, de Weck et al. [35] conducted a study on the Iridium communication satellites to highlight the dangers of relying on forecasts. In this case, the constellation of satellites were deployed and optimised for a single demand projection. This would be fine if the predictions were met and demand was kept within margins. However, demand was not met, there was insufficient uptake of the technology and the project failed, not technically, but financially leading to bankruptcy. De Neufville & Scholtes [36] also highlights this through a parking garage example to illustrate asymmetric risk and shows that, while it is difficult to increase capacity of a system once deployed, it is easier to not fill capacity. Instead, both de Weck and de Neufville suggests flexibility to mitigate risk whilst allowing the system to take advantage of opportunities. That is, instead of designing for a robust system to meet some demand projection, the system can be designed such that it can change its design in the future. In the study by de Weck et al [35]. it was shown how flexibility and phasing the deployment of satellites could have saved 20%. While a flexible solution of phasing may not have prevented bankruptcy, the study highlights the dangers of relying and building for fixed projections.

These three properties are thus related through uncertainty, time and cost. The challenge in designing large-scale engineering systems for resilience therefore involves balancing system properties to address these factors. As a system is designed for the further future, the uncertainty increases which in turn increases cost. Furthermore, decisions have to be made in order to best traverse the uncertainty and performance bounds of each design solution. From the previous discussion, it is apparent that robustness and adaptability serve uncertainties in the immediate or predictable future. It can be therefore seen that these two properties form an initial "total" robustness of the initial design to handle foreseeable uncertainties. This has to be balanced against flexibility for completely or partially unforeseeable uncertainties so that resilience may be achieved.

5. Conclusion

In order for a large-scale engineering system to be designed for resilience, it has been found from literature that the system has to absorb disturbances, adapt for change and thrive for the future. This can be related to the system properties robustness, adaptability and flexibility. Robustness involves being insensitive to disturbances from the environment provided the system stays within designed margins while adaptability was found to have a duality in meaning. In one sense, adaptability could refer to the system recovering back to an initial system state and in another sense, adaptability could mean to transfer between different system states such that the system can perform for different requirements.

These three properties can be related through uncertainty, time and cost. However, it was apparent that robustness and adaptability had to be designed for uncertainties in the immediate future and at the time of system deployment while flexibility focused more on strategy for future development of the system. As such, robustness and adaptability were grouped to form a "total" robustness of the system which described the uncertainty margin the system can withstand in the near future. In order to enable a large-scale engineering system for resilience, the cost and needs for the immediate future, addressed by "total" robustness, has to be balanced with the cost of flexible strategies to address uncertainties in the further future.

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