

## Toward a resilient manufacturing system

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### ABSTRACT

Resilience often refers to a property of social and ecological systems. Recently, resilience is applied to engineered systems, referring to their capability to recover their functions after partial damage to lead to successes from failures. In this paper, the concept of engineering resilience is revisited and clarified. A new definition of the general production system is proposed, upon which the concept of the resilient manufacture system (RMS) is proposed. Furthermore, four guidelines for design and management of the RMS are proposed. Examples are discussed to illustrate the applications of these guidelines toward the RMS.

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### 1. Introduction

In this paper, a new behavioural property of manufacturing system, resilience, is discussed. Resilience in the context of manufacturing systems is less discussed in literature. Holling [1] discussed the difference between engineering resilience and ecological resilience, where he considered that the engineering system has one equilibrium state only, while the ecological system has more than one equilibrium state.

The resilience property is a promising property for today's manufacturing systems in terms of achieving a sustainable success of the systems [2]. The resilience property is associated with what, how, and why a system behaves when facing failures in the system. In particular, a resilient system will behave to move from failure to success. Because failure is perhaps an inevitable event to today's manufacturing systems, development of the resilience property into the manufacturing systems is imperative [2].

The objectives of this paper are: (i) presenting a more accurate understanding of the resilience property of a manufacturing system out of other properties of the system and (ii) proposing principles for design and management of resilient manufacturing systems today.

There have been few studies relevant to the foregoing objectives of this paper, which can further be classified into definition, measurement, analysis, synthesis, and management. In the definition of resilience, Pulley and Wakefield [3] defined resilience, in the context of building a system, as: "resilience provides the ability to recover quickly from change, hardship, or misfortune. It is associated with elasticity, buoyancy, and adaptation." Hollnagel et al. [4] defined resilience, in the light

of its implication to safety management, as: "resilience is the ability of an organization (system) to keep or recover quickly to a stable state, allowing it to continue operations during and after a major mishap or in the presence of continuous significant stresses." Hollnagel et al. [4] further stressed on the role of prediction of mishaps of the system as part of the scope of resilience engineering in an extended definition of resilience engineering. In the context of enterprises, Guelfi et al. [5] defined the resilience as the capacity of a business process to recover and reinforce itself when facing changes. Further, in the context of businesses, Hamel and Valikangas [6] considered the resilience as an ability of firms to change from failure to success.

Regarding the measurement, analysis, and modelling of resilience, Gao [7] presented an approach to modelling and analyzing the resilience property. The basic idea of the approach is to view a system under analysis as a network. The system performs a certain function, say F. Each time one or more nodes of the system are removed, the total number of the possibilities for the system to reconfigure with the reduced network to still achieve the function F is examined. This number is a measure of the resilience property. Regarding the synthesis and management of resilience, guidelines with a check-list style are proposed according to Gao [7]. In short, understanding of the engineering resilience is still in its infancy and knowledge for analysis, design, and management of resilient systems is scarce.

This paper is focused on the concept of resilience and design and management of the resilient manufacturing system (RMS) to achieve the two objectives as mentioned before. The organization of the paper is as follows. Section 2 presents the concept of resilience in the context of manufacturing systems along with a new conceptual model of them. Section 3 presents guidelines for designing and managing the resilient manufacturing system. Section 4 gives examples to illustrate these guidelines. Section 5 concludes the paper.

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## 2. Resiliency of manufacturing system

### 2.1. Manufacturing system: a resilience perspective

Despite an enormous amount of researches on manufacturing systems, the authors feel that a suitable one with which to start to understand resilience in the context of manufacturing or production systems is missing in literature. Therefore, we begin with a proposal for a model of the general manufacturing system.

Fig. 1 shows a semantic model of the production system – in particular attempting to capture a set of core and common features among all production systems at different levels such as shop-floor level and enterprise level. From Fig. 1, it can be seen that the system has two layers in structure: infrastructure and substance, and the substance is constrained by the infrastructure. The infrastructure can be a human system, machine system, or human-machine system. The substance can also be a human system, or material system, or signal. Materials are goods or products, humans are learners, and data or signals carry knowledge and information. An assembly robot is an example of infrastructure, and parts manipulated by the robot are substances. Users receive substances and can be humans, machines, or ecological systems as well. Resources can be energy, materials, or data [8]. Further, both the infrastructure and substance systems include a manager, respectively. The role of manager can be one of the four ones, namely, planning or scheduling, controlling, leading, and coordinating, depending on the level of the system. For the robot in the context of an assembly line, the control system or controller of the robot is such a manager. The manager of the substance system primarily performs planning, scheduling and controlling tasks.

The foregoing semantic model is both general and generic. The sense of generality is that the model captures all aggregate properties of any specific production system. For instance, if the infrastructure is human, the resource is data or signal and substance is human, the system is a training system. That is to say, the model of Fig. 1 can represent a training system. If the infrastructure is machine and resource is material, the system as represented in Fig. 1 is a conventional machine-oriented production system. The sense of generic is that the model captures the common characteristics of any manufacturing system at the highest abstraction level. For instance, each manufacturing system must have something as input, an infrastructure, something as output that further meets the user's need, and generates impact to the surrounding system which may contain humans, machines and ecological systems.

Fig. 2 further captures the network nature of a production system, in which there are two interdependent production systems. From this figure it can be found that (1) the network may include not only directed links but also undirected links (e.g., link 1) and (2) the loop may exist not only within one production system but also across the two production systems. For instance, within one production system (production system 1), a human may on one hand be a customer or user (buyer of car) but on the other hand be a part (assembly operator on the car assembly line) of the infrastructure system (car assembly system). Examples of the relations as indicated in Fig. 2 are taken as follows: Relation 1: two production systems make use of the same energy resource; Relation 2: A sub-assembly as a material output in production system 1 becomes a material resource in production system 2; Relation 3: A machine as a part of surrounding in production system 1 is a part of the infrastructure in production system 2;

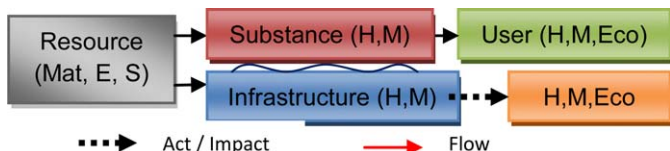


Fig. 1. Semantic model of general and generic production systems. (Mat: material; E: energy; S: signal; H: human; M: machine; Eco: ecological.)

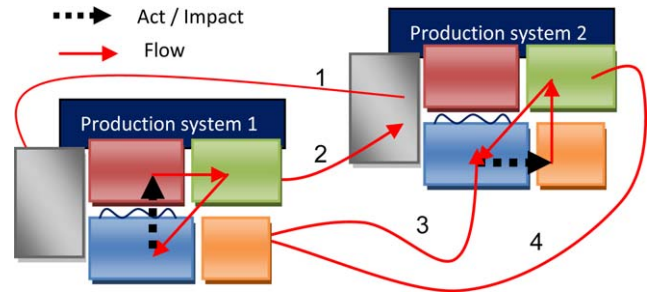


Fig. 2. The network nature of a production system. (Relation 1: production system 1's resource share with production system 2's resource. Relation 2: output of production system 1 serves as a resource for production system 2. Relation 3: the effect of the infrastructure of production system 1 connects to the infrastructure of production system 2. Relation 4: output of production system 2 affects the infrastructure of production system 1.)

Relation 4: a human as a part of the surrounding in production system 1 is a user in production system 2.

The semantic models of Figs. 1 and 2 need to be represented in a more formal way, and further a sufficient level of details of the infrastructure and/or substance may need to be represented. At this point, we propose a twin-FBS (function–behaviour–structure) formalism to translate the semantic model to the twin-FBS model.

### 2.2. Twin-FBS model of the production system

Since the 60s, in the fields of artificial intelligence and design, the concepts of function and structure, which were widely used in biology and sociology, have been extended to the concepts of function, behaviour, structure, which is called FBS (function–behaviour–structure). Under the name of FBS, however, there are several different understandings of FBS with inclusion of new concepts, e.g., whether the concept of state should be used as opposed to the concept of structure, whether the concept of purpose makes sense and should be included in the FBS model, whether the requirement should be included in the FBS model [9] etc. A comparison of these variations is given by Zhang et al. [10]. A more complete FBS has been developed by Lin and Zhang [11] by including structure, state, behaviour, function, principle, context, sometimes named FCBPSS where F: function, C: context, B: behaviour, P: principle, S: state, S: structure. Among these concepts, the notions of context and principle are worth further explanation here. The principle concept refers to effects, laws, axioms that govern the behaviour (which is further defined as: relations among state variables). The context concept refers to environments and interfaces that surround a particular system, which define specific functions of the system [10].

Perhaps the first attempt to apply the FBS to conceptual modelling of complex dynamic systems was made by Lin and Zhang [11]. The FBS approach has been successfully applied to the telecommunication system by He [12]. In this paper, the FBS approach is further taken to model both the infrastructure and substance, which then leads to the twin-FBS model. While the FBS for the infrastructure is similar to those conventionally used in design and management of artefacts and dynamic systems, the FBS for the substance may warrant further remarks. The state of the substance system refers to the property of the substance which flows under the constraint of the infrastructure system. The principle of substance refers to the laws and effects that govern the behaviour of the flow of substance.

The relationship between the FBS of the infrastructure and the FBS of the substance will also be represented in the twin-FBS model which follows the concept of relationship in the well-known entity-relationship model in conceptual data modelling.

### 2.3. Resilience of production systems

Resilience is related to the recovery from failures. Therefore, first of all, different types of failures should be elaborated. This can

be done with respect to the representation of the production system as shown in Figs. 1 and 2. The first type of failure is that the user's demand is not satisfied, which has further two situations: (a) the amount of substances is more than the demand (or substances do not have any user) and (b) the amount of substances is less than the demand. The second type of failure is that the required resource is not available (or not sufficient). The third type of failure is that the structure of infrastructure is partially damaged. The fourth type of failure is that the structure of substance is partially damaged. The fifth type of failure is that the operation of infrastructure harms the human, machine and ecological system.

According to the previous discussion of the resilience concept in Section 1, resilience of the production system means the system's capability of leading to success from failure on the system's own – in particular its own infrastructure, substance. There are several remarks regarding this definition.

**Remark 1.** We do not require that the system performs the same function as before but success in the sense that the system provides a substance to have a user per se.

**Remark 2.** We do not consider the resource and user of the system as a potential means to improve the resilience of a manufacturing system for simplicity.

**Remark 3.** The resilience differs from the reliability in that the reliability is a property of the system to measure the life of the system (i.e., sustaining success of the system), and the resilience differs from the robustness in that the latter is a property of the system to measure the insensitivity to disturbances of the system when the system is in operation.

**Remark 4.** The definition of resilience proposed in the present paper differs from one of the Hollnagel et al. [4] in that the latter considers the recovery as the system returning to a stable state. The stable state of the system is, however, not a necessary condition to make the system a success from a failure. The present definition also differs from [6] in that the latter, though using the phrase of 'from failure to success', does not mention various types of failures. It is indeed that for all the definitions of resilience in the literature, in case of applying them to production systems, lack the perspective of the production system as described in Figs. 1 and 2 of the present paper, which is an inherent limit of applying them to a theory of resilience of production systems.

**Remark 5.** Holling's definition [1] of engineering resilience is obsolete, as the current science and technology for engineering has allowed the system to work for the same function in different states. For instance, Bi and Zhang [13] has shown that different assemblies of modules that follow a modular architecture can fulfil the same function. A buzz word 'reconfigurable' X seems to be another evidence of the point that engineered systems may be able to work in different states.

### 3. Principles for design and management

This paper focuses on the theory and methodology to design and manage a resilient manufacturing system. Based on the theory proposed by Zhang and Lin [14], we propose the following guidelines useful for design and management of the resilient manufacturing system.

*Guideline I: Redundancy at large (design):* The architecture of a resilient system should include redundancy. The notion of redundancy is well known in the literature [15] but is not readily applicable to the context of engineering resilience. Three types of redundancy are proposed to develop the resilience property of the production system. Type I: there is a physical component or system (say A) which is a duplicate of another one (B) in the system, and when B in dysfunction, A is put in place. Type II: A and B are both in operation, and A does not run out of its full capability or capacity

such that the part of A can be trained to fulfil the role or partial role of B. The situation can be of a more general situation where B can be more than one component or system and so can be A. Type III: A particular infrastructure can be used for more than one substance. It is noted that type I of redundancy is well known in reliability enhancement for critical dynamic systems such as aircrafts.

*Guideline II: Total function (management):* Each component or subsystem can potentially play multi-roles. The nature of a specific role which is played by the system per se is a result that the system's general function or behaviour [10] meets the specific context – that is the pre- and post-condition for the specific component or subsystem. To enhance the resilience property, both the general function and specific function of each component or subsystem along should be specified and known. It is noted that the concept of general function and specific function is known to the systems design, an important part of the systematic design approach [16], but is first used here to relate it to resilience engineering.

*Guideline III: Learning and training (management):* The learning and training (LT) component works with the second and third types of redundancy as discussed above, and its role is self-explanatory. One remark is that the LT component is also expected to perform learning and training for unexpected possibilities in reconfiguring the system in responding to failures. This feature is imperative to deal with unexpected failures caused by external mishaps and natural disasters. Bringing the learning and training in a resilient system is learned from rehabilitation of neurological patients [14].

*Guideline IV: Ontology modelling:* There is a need of the ontology model for the RMS. Ontology of a manufacturing system refers to concepts and their relationships in a specific business context. The concepts may be related to each other in a hierarchical manner. An ontology model is a data representation of the ontology and it provides the governing mechanism for reconfiguration. Furthermore, reconfiguration may be related to both the infrastructure and substance, therefore, an integrated design of the infrastructure and management of the substance is necessary. It is believed that ontology provides a source of knowledge for a computational model of the RMS for achieving a prescribed resilience.

### 4. Illustrations

In this section, we present simple examples to illustrate the application of these guidelines to improve the resilience property.

**Example 1.** There are various email systems and they often co-exist in enterprise systems, for example, 'webmail' and 'outlook'. The two systems can be specified by the user to correspond to the same amount of data while at the same time to specialized data of the each, respectively. The two systems can be switched to each other. As such, when one system is damaged for some reason, the user can readily use the other to continue the email communication operation. This example can be viewed as one resulting from Guideline I.

**Example 2.** Fig. 3 shows a machine which is a kind of infrastructure. The machine has two servomotors, four moving components and one ground frame. The machine performs a task to hold a part and to move it by following a desired trajectory at point P. There is software with this machine system, and the software system is responsible for real-time instruction of the supply of energy (electronic current with constant voltage) to the motors of the machine. Suppose one servomotor is partially broken at one point of time; in particular the partially broken servomotor is assumed to still function as a constant velocity motor. As such, the system has one constant velocity motor and one servomotor, and such a system is called hybrid actuation system [17]. The hybrid actuation system can still perform the required function of the original machine with two servo motors by reprogramming the control

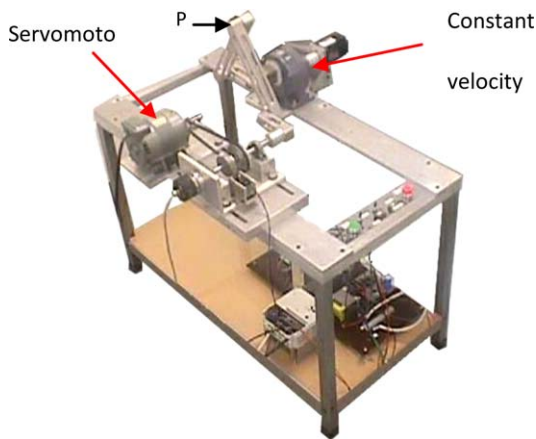


Fig. 3. Resilient infrastructure systems. (Constant velocity motor results from the servo motor which is partially damaged.)

software of the system [17]. This resilience gained in this way follows Guideline III.

**Example 3.** An emergency evacuation is to move victims from a risk place to a safe place [18]. It is assumed that a part of the roads are damaged. A plan needs to be generated to determine an optimal route for victims. The optimal route also includes contraflows that change the direction of the original flow of victim transportation in the road system (e.g., highway). In this example, the infrastructure is the road, and the substance is the human. In this work, a twin-FBS model for the system in interest is created, which provides the ontology of the variables and an optimization model [18]. The variables include the road (i.e., construction of a new road or repair of a damaged road), the amount of victims, type of victims, and multi-destinations. The resilience property of this emergency system is enhanced by such an integrated road repair (design) and contraflow routing (management) approach to evacuation of victims. This example shows the design which follows Guideline IV.

## 5. Conclusion

This paper elaborated the concept of resilience especially engineering resilience. Holling's view [1] that engineering resilience has only one state was extended to the view that both engineering resilience and ecological resilience could have more

than one state. It was noted that states in the engineering system may be called configurations. This paper also provided a new description of the manufacturing system, from which various failures can be identified and thus the resilience property of the manufacturing system can be more thoroughly defined. Upon the clarification of the resilience concept and the new definition of the manufacturing system, guidelines for design and management for enhancing resilience were proposed. Several examples were discussed to illustrate the use of these guidelines. It can be concluded that the resilience property of a production system is an important property that exhibits its capability to get success from failure.

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