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Supply chains' robustness: Challenges and opportunities

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Abstract

Nowadays robustness of supply chains, i.e. their ability to cope with external and internal disruptions and disturbances, gains more and more importance. The paper puts the topic into a broader scope, i.e. it also highlights the concept of robustness in other disciplines (especially in biology) and at the different levels of manufacturing. The main risks of supply chain operations together with some fundamental risk mitigation strategies are summarized. Measures of structural and operational robustness of supply chains are introduced, and the concept of a framework for evaluating supply chains' robustness, complexity and efficiency is described in short. Challenges and opportunities related to the increase of robustness are outlined in the paper, with special emphasis on those which arise in the cyber-physical era.

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Keywords: Robustness; Complexity; Efficiency; Supply chains and networks; Cyber-physical production and logistics systems

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1. Introduction

Robustness became a fundamental requirement at every level of the production hierarchy from the process / machine level, through the system and enterprise levels, up to the level of supply chains and networks. Before concentrating on the supply chain related issues, in Section 2 the concept of robustness is investigated in biology and in the different domains of manufacturing. The main risk types the supply chains are facing, and some fundamental risk mitigation strategies are summarized in Section 3. Moreover, the structural and operational robustness of supply chains together with some of their quantitative measures are introduced. Section 4 outlines the concept of a framework for evaluating supply chains' robustness, complexity and efficiency in order to achieve trade-offs between these different aspects. In Section 5 the challenges and opportunities the cyber-physical era brings for supply chains' robustness are summarized. Finally, the conclusions are drawn in Section 6.

2. The concept of robustness

The concept of robustness can be found in different disciplines, e.g. in biology, economics, architecture, computer science, systems and control science, and – naturally – in mathematics (e.g. robust optimization).

2.1. Robustness in biology

As to the *biological robustness*: "robustness is a property that allows a system to maintain its functions against internal and external perturbations" [1,2]. "To discuss robustness, one must identify system, function, and perturbations. It is important to realize that robustness is concerned with maintaining functions of a system rather than system states, which distinguishes robustness from stability" [2]. Biological robustness – according to the kind of perturbation – can be classified as mutational, environmental, recombinational, behavioral, etc. one.

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It is argued that robustness is a fundamental feature of evolvable complex systems, and evolution enhances the robustness of organisms, e.g. by increasing their complexity through successive addition of regulatory systems. Trade-offs between robustness, fragility, performance and resource demands can be observed in biological systems at different levels. Bacteria, for example, should be able to swim faster without negative feedback, but this would sacrifice their precision in following a chemical gradient: the use of negative feedback improves the bacteria's ability to follow the gradient, at the cost of reduced swim speed [1].

In biology, the following "solutions" are distinguished to ensure the robustness of a system [1]:

- *System control*: negative and positive *feedbacks*, for robust adaptation to perturbations, and for amplification of stimuli, respectively.
- *Alternative or fail-safe mechanisms*: for achieving *redundancy* by several identical or similar components or modules able to replace the one which fails, or by diversity or heterogeneity, whereby a specific function can be attained by other means available in a population of heterogeneous components.
- *Modularity*: for containing perturbations and damage *locally* to minimize the effects on the whole system.
- *Decoupling*: for isolating low level variations from high level functionalities. *Buffers* play a specific role here, e.g. Hsp90 (heat shock protein 90) decouples genetic variations from the phenotype, providing a genetic buffer against mutations.

2.2. Robustness types

The concept of robustness can be categorized by using its different characteristics:

- Robustness *in the small* versus robustness *in the large* depending on the – problem specific – magnitude of the perturbations.
- A similar distinction is made between *local* and *global* robustness, i.e. whether the whole uncertainty space or a relatively limited part of it is considered in the investigations (cp. local versus global optimization).
- *Active* versus *passive* robustness, i.e. whether a modification in the control is necessary or not, in order to preserve the specified properties.
- *Proactive* versus *reactive* robustness, i.e. whether measures are taken before something disruptive happens or after it.

2.3. Robustness in manufacturing

Robustness becomes a more and more important feature at the different levels of manufacturing.

In *product design* robustness is tackled by making the product insensitive to variations, e.g. the environmental variation during the product's usage, the manufacturing variation, and the component deterioration (Robust design or Taguchi method [3]).

A *manufacturing process* is considered robust if it maintains its acceptable performance consistently at a desired level, even if there may be significant and substantial changes occurring in input variables and noise parameters during a given period of time or planning horizon [4]. Naturally, process monitoring and (adaptive) control play a significant role here [5,6]. A comprehensive list and categorization of approaches to measure and evaluate the robustness of manufacturing processes is given in [4].

For a *manufacturing system*, robustness can be defined as the system's aptitude to preserve its specified properties against foreseen or unforeseen disturbances [7].

A fundamental way to increase the robustness of manufacturing systems is to allocate reserves in physical and / or time domains (buffers, inventories or slack times). Another group of approaches relies on different (robust, reactive, predictive-reactive, proactive) scheduling techniques.

Distributed, decentralized control solutions – from their nature – offer higher robustness level for the system. The agent-based, holonic manufacturing systems (HMS) consist of autonomous, intelligent, flexible, distributed, cooperative agents or holons [8,9,10]. The basic approach can be augmented with coordination and control mechanisms inspired by biological systems (i.e. food foraging behavior in ant colonies) supporting the execution of process plans properly under changing conditions, by continuously forecasting the workload of the manufacturing resources and the lead times of the products [9].

The concept of Biological Manufacturing Systems (BMS) aims to deal with dynamic changes in external and internal environments based on biologically-inspired ideas such as self-growth, self-organization, adaptation and evolution [11,12,13]. It belongs to those, more and more frequently adopted approaches which use analogies taken from the biology to develop more effective and robust products and systems.

In [14] the importance of the cooperation between different entities at various levels of manufacturing for realizing more robust and responsive systems is underlined.

3. Supply chains' robustness

3.1. Main risks of supply chain operations

Supply chains are exposed to *risks* of different kinds. *Demand-side*, *supply-side* and *catastrophic risks* are distinguished in [15].

Demand-side risks originate in disruptions emerging from downstream supply chain operations. They can manifest in the physical distribution of products to the end customer (e.g. transportation problems, or improper functioning of the warehouses), or they can come from the mismatch between the forecasted and the actual demands or from the inappropriate supply chain coordination. The well-known bullwhip effect, i.e. the amplification of the demand volatility in the upstream direction of the supply chain is such a characteristic phenomenon. The possible negative consequences of demand-side risks are costly shortages, obsolescence and inefficient capacity utilization.