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ScienceDirect
Procedia CIRP 19 (2014) 87 – 92
www.elsevier.com/locate/procedia

Robust Manufacturing Conference (RoMaC 2014)

The concept of robustness in production systems and its correlation to disturbances

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Abstract

The paper first presents an approach to classify different understandings of the term robustness. The classification is based on a literature review which discusses the term robustness and its correlations to the terms flexibility, resilience and risk. Thus, the similarities and differences in the understanding of robustness, flexibility and resilience will be shown and an own definition of robustness will be derived from these investigations. Given the definition of robustness, it is crucial to determine the entities against which a production system needs to be robust. In order to do this, this paper will focus on the different kinds of disturbances that pose a risk to the production system in its operational and tactical work. Finally, a first approach to analyze robustness is outlined.

Selection and peer-review under responsibility of the International Scientific Committee of "RoMaC 2014" in the person of the Conference Chair Prof. Dr.-Ing. Katja Windt.
Keywords: Robust Production Systems, Disturbances

1. Introduction

Today's global production networks have to fulfil the given market's demand for a high level of performance. The performance can be measured using different key performance indicators (KPI) and is subject to the given environmental conditions and disturbances. The production networks face lots of disturbances which pose a need for robustness. In order to increase the robustness of a global production network, the communication and interaction between the individual partners need to be improved and each partner in the global network needs to increase its robustness.

This paper will focus on the latter. An individual partner is robust if all its production systems always fulfil the given demands despite varying working conditions and disturbances in the global network. The first level of investigation on robustness is thus the level of production systems. Production systems need to reach a certain level of performance in order to fulfil the given demands. However, they are subject to many different kinds of disturbances which affect the system's performance. Therefore, not only the mere KPIs of a production system but also their stability are a relevant feature for a successful production in a global network. So, the robustness of a production system will be increased if its KPIs are permanently on a high level. These considerations are based on the definitions of robustness and disturbances and will be the basis for further work.

The paper is organized as follows. In chapter 2 the term robustness and its relations to other terms is examined, while chapter 3 focuses on the disturbances to which a production system is exposed. Based on these considerations, chapter 4 presents an approach for measuring the robustness in production systems.

2. Definition of the term Robustness

In order to generate a common understanding of robustness in this paper, the definition of robustness and its correlations to other relevant terms are discussed. A robust production system has to be able to deal with disturbances in order to keep its performance on a high level. This can either be done by being resistant to disturbances (resilience, agility) or by an

Selection and peer-review under responsibility of the International Scientific Committee of "RoMaC 2014" in the person of the Conference Chair Prof. Dr.-Ing. Katja Windt.
doi:10.1016/j.procir.2014.04.078

appropriate reaction to differing conditions (flexibility, changeability). The similarities and differences of the terms resilience, agility, flexibility, changeability and performance will be shown and a definition of robustness will be derived from this investigations.

2.1. Robustness

The general term of robustness is used differently in literature. However, there is a common idea of robustness which builds the basis for most of the existing definitions: robustness describes the stability against different varying conditions (see for example [1], [2], [3]).

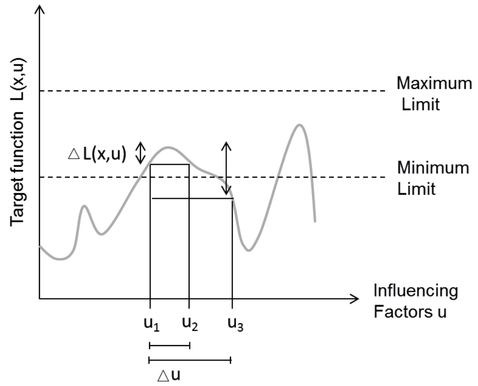

Fig. 1. Target function of a solution *x* under varying influencing conditions *u*.

If a possible solution x to a problem leads to a stable target function value $L(x,u)$ under varying conditions Δu, it is a robust solution. Different authors have different ideas on the demanded stability of the target function value and consider various kinds and scopes of influencing conditions. The influencing conditions Δu have huge effects on the deviation of the target function value $L(x,u)$. The more different conditions are considered, the bigger the deviation in the target function value will be. The accepted thresholds in deviation of the target function depend on the author's understanding of stability. Therefore, especially the specific understanding of stability is decisive for a categorization approach of the different ideas of robustness. For all approaches the absolute values of the target value function for different influencing conditions and/or the deviation of the target value function within all regarded influencing conditions is decisive.

According to their understanding of stability most approaches can be classified into the following three categories focusing different aspects.

Feasibility of a solution (1)

A solution x is robust if it is feasible for all regarded varying conditions (e.g. [4]) unlike its target function value or its deviation.

Deviation of the target function (2)

Other approaches focus on the deviation of the target function under different influencing factors. If the deviation is small enough, the solution is robust (e.g. [5]). By limiting the deviation, the absolute difference in the target function value always depends on the dimension of the target function value.

Absolute value of the target function (3)

A solution x is robust if its target function value fulfills the given requirements for all regarded varying conditions (e.g. [2], [3]). The requirements can be expressed as a demanded minimum and/or maximum limit out of which the target function value may not fall, or simply as a still acceptable value of the target function which isn't specified precisely. The deviation of the target function value is not explicitly regarded in this category. As for all categories, it is crucial to define the regarded range of influencing factors. Considering a wider range the target function value may exceed the given limits (see Fig. 1). Thus, fixed limitations can only hold for a predefined range of influencing factors and need to be adapted for any changes in the regarded problem.

The feasibility requirement (1) should always be fulfilled. It should be enhanced by further requirements as in category (2) and (3). Category (2) focuses on a solution's deviation So, a solution with a small target function value can be robust, if its deviation is small, too. Category (3) focuses a solution's function value. The deviations don't matter as long as the target function doesn't exceed the given limits.

Given the different ideas of the approaches, robustness should not only include a solution's stability, but also its performance.

2.2. Performance

Despite the different categories, the robustness of a system is always linked to its stability and target function as mentioned in section 2.1. For many authors the target function describes the system's performance (see for example [22]).

For performance measurement, many different key performance measures exist which can be used as a target function [23]. In many cases, however, a single key performance indicator (KPI) does not represent all relevant information on the system's performance. According to this, the concept of robustness can be enlarged to the use of multiple key performance indicators in one or several target functions. The stability demands as categorized above are not affected by this expansion.

2.3. Flexibility and Changeability

The term of robustness is often related to flexibility. Robustness can be seen as a measure for a system's flexibility in case of changes and uncertainties [6]. So, flexibility is an enabler for robustness [7]. A flexible reaction on different disturbances reduces their negative effect on a production system's performance.

Unfortunately, flexibility is used even more divers in literature than robustness. [8] gives an overview of different kinds of flexibility described in literature. Many flexibility kinds help to adapt to varying conditions and thus support the robustness of a system.

For [9] flexibility is one type of changeability which focuses on the production segment. Other authors like [10] distinguish between flexibility and changeability. Flexibility only allows for adaptations within limited flexibility corridors. Changeability goes beyond the adaptations of flexibility and enables changes between the flexibility corridors.

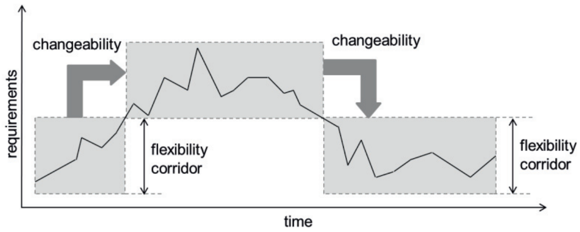

Fig. 2. Relation of Flexibility and Changeability according to [10].

As the varying conditions regarded in this paper focus on short- to medium-term disturbances, the robustness of a local production system is enabled by its flexibility. Possible adaptations in the field of changeability mostly refer to adaptations that take place on a network level or integrate costly long term adaptations. Both criteria are out of the scope of this paper.

2.4. Agility

According to [11] an agile production system has the ability to change predefined given system states in order to adapt to unpredictable disturbances. Agility is the ability to obtain competitive production in a plant. The main difference between agility and flexibility is that agile practices are not defined a priori. An agile production system converts quickly and smoothly without predefined or planned adaptation methods. Consequently, not all potential disturbances need to be known in advance as alternative courses of action are instantly developed when the disturbances occur. So, agility enables for adaptation to bigger disturbances than flexibility does [11].

In the context of agility, [12] refers to the entire production network. The network can adapt by quick changes in cooperation. The quick adaptation to changes in demand allows to deliver the products in time. This requires a flexible, computer-based infrastructure within the network condition. A production system itself can improve the network's agility by implementing changeability. This understanding is supported by [9] for whom agility is the highest level of changeability. Agility is related to the network level and thus also out of the scope of this paper which focusses on production systems.

2.5. Resilience

Resilience is mostly regarded as the ability of a production system to tolerate disturbances (see for example [13], [14]). While disturbances occur, the system can either adapt to the new situation [15] or be resistant towards disturbances without adaptations [16]. Most authors include the adaptation to new situations in their understanding of resilience. The methods for adaptation, however, are not commonly defined. The specific actions seem to depend on the nature of the disturbances. In case of minor disturbances, the system shall be resistant without any actions (see [16]). If disturbances affect the equilibrium state of the production system the production system shall regain its original state as quickly as possible (see for example [17], [18], [19]). A permanent change of environmental conditions however, can include ongoing adaptations [20] which may not lead back to the system's original state in the short term.

Overall, the idea of a resilient system comes very close to the idea of a robust system for many authors.

2.6. Risk

Risk is the effect of uncertainty on objectives [21]. Given this definition, risk is closely related to robustness. If the given uncertainty (e.g. varying conditions) has only little effect on the production system, the system is robust. So, an increasingly robust production system is decreasing the risk it is exposed to.

For risk reduction two approaches exist according to the risk matrix. Either the undesired effects of an unexpected event or a varying condition can be diminished or the probability of its occurrence can be reduced (see Fig. 3).

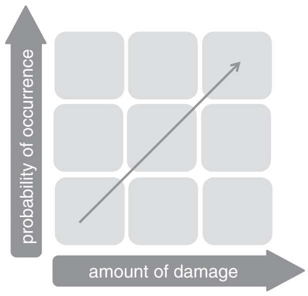

Fig. 3. Risk Matrix with the Direction of rising Risk (following [37]).

Both aspects of risk reduction will lead to an increase in system robustness. On the one hand, a diminished effect in case of varying conditions is similar to the demanded stability. On the other hand, if a production system can inherently reduce the probability of undesired conditions and events, it also becomes more robust.

2.7. Robustness of Production Systems

The paragraphs above give an overview on the field of robustness and show its links to other terms. Fig. 4 illustrates the correlations between the mentioned terms.

Flexibility and resilience come very close to the term of robustness. Due to the regarded scale of a production system and the focused operational/tactical effects in this paper, the terms of changeability and agility are not within the focused scope of robustness.

Risk has an effect on the regarded performance of a production system which is mostly negative. Therefore, the given risks motivate an increase in robustness of production systems.

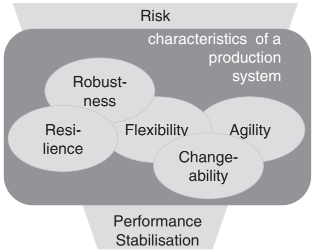

Fig. 4. Assumed Correlations between Robustness, Resilience, Flexibility, Changeability, Agility, Performance and Risk.

The robustness shall stabilize the systems performance in case of varying conditions (risk). In case of an unexpected event this has a positive effect on the system's performance. But the activities which increase the robustness could have negative effects on the systems regular performance in stable conditions. So, a tradeoff between the system's stability in case of varying conditions and its regular performance is needed. These considerations lead to an understanding of robustness which combines category (2) and (3) of section 2.1. As the deviations of the target function value strongly depend on the regarded influencing factor, it is difficult to implement appropriate robustness limits. Therefore, robustness cannot be equal to stable or consistent performance. Robustness should rather aim for a minimization of the deviation while keeping the level of performance as high as possible. Herein, robustness does not only demand a stable solution (with little deviation), but also regards the solution's absolute target function value. Only by an integrated consideration of both aspects a good and stable solution can arise, which will be referred to as a robust solution in this paper.

Given the understanding of robustness it is crucial to know against which entities a production system needs to be robust. The regarded range of influencing factors has a huge influence on the deviation of the system's performance. Therefore, the paper will now focus on the different kinds of disturbances that pose a risk to a production system.

3. Disturbances

In order to examine the possible disturbances which influence a production system, it is crucial to define what is meant by the term disturbances. Therefore, the term will be defined as it is understood in this paper.

3.1. Term of Disturbances in Production Systems

The term disturbances is widely used in literature (see for example [24]). The different definitions of disturbances have many similarities but differ in important details (see Fig. 5).

Common within most definitions of disturbances are deviations from a planned production or planned values in the broadest sense. One difference in the understanding of disturbances, however, is whether the author refers to a disturbance when talking about the event which leads to the deviation [25], [26], or about the deviation itself [27].

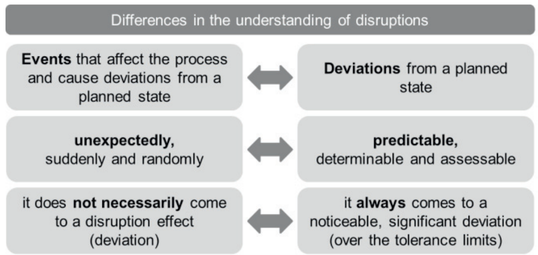

Fig. 5. Differences in Understanding of Disturbances in Literature.

Other authors include both the event (cause of disturbance), as well as the deviation (disturbance effect) in their definition [28], [29]. Further differences exist mainly in the foreseeability of the disturbances and the extent of their effect. For some authors disturbances are unexpected, sudden or even random events [25], [26]. For others, only the time of occurrence is not predictable, determinable or assessable. Only for [30] disturbances are assessable. So, for most authors disturbances are unpredictable, either in their type or in the time of their occurrence.

[29] distinguishes between the cause of a disturbance and its effect. He states that a disturbance does not necessarily lead to an effect. However, the majority of authors consider a noticeable or substantial deviation to be a necessary characteristic of a disturbance [28], [31], [32].

Fig. 6. Phases of a Disturbance (according to [28]).

Disturbances have a dynamic character. The course of a disturbance can be divided into two phases: the latent phase and the manifest phase (Fig. 6) [28]. The latent phase starts with the occurrence of the fault cause and ends with the onset of the disturbance effect. Subsequently, the manifest phase follows. It lasts until the end of the disturbance and includes the reporting time, the coordination and waiting time, the time of diagnosis and the time for disturbance suppression. The latent phase corresponds to the time range of an existing buffering, since it only leads to noticeable deviations and thus a disturbance effect, if this buffer is depleted. Due to the Lean-trend for reduction of buffers and safety stocks, the latent phase is increasingly shortened and thus the time to react before the disturbance effect realizes is shortened. [28]

Given these considerations, in this paper a disturbance is defined as follows:

A disturbance consists of a cause and an effect. The disturbance occurs

- unintended and unwanted,
- unplanned: unexpected and unforeseen or with unknown time of occurrence.

The effect is a significant deviation between the actual and planned values and manifests itself as a failure or defect (quality, quantity, time delay) of input, output or throughput. The disturbance mostly has a negative influence on at least one of the three dimensions cost, time, quality.

3.2. Sample Disturbances and their effects

According to the given definition of a disturbance, several possible disturbance scenarios can arise in a production system. Table 1.1 gives a few sample disturbances as they are found in literature.

Table 1. Sample Disturbances of a Production System.

Disturbance	Literature
(sudden) machine and equipment failures / equipment defects / non-functioning equipment	[27],[28], [30], [31], [32], [33], [34], [35]
defective / precipitation of tools / tool breakage	[30], [34]
lack of planning in tool change and provision of tools	[26]
absence / lack of staff	[26], [34], [35]
work failure / incorrect operation / inappropriate treatment	[28], [30], [33]
temporal distortions of goods receipts / delays / deployment delay	[29], [27], [35], [36]
(sudden) loss of suppliers	[28]
change in customer demands	[36]

As can be seen in the given extract of disturbances known in literature, many different kinds of disturbances may arise. Some disturbances have long-term effects (e.g. loss of suppliers) others rather have short-term effects, like the delay of an order. Besides, the duration of the effects the disturbance cause is different. Some lie within the regarded system boundaries, others do not. As the system boundaries of this paper are the local limits of the regarded production system, the disturbances caused on a supply or customer site are exogenous while the others are endogenous. In reality, the possible disturbance causes are even broader than the ones known in literature. In order to consider the robustness of a production system, however, the dimension of regarded disturbances needs to be known in advance. As mentioned in chapter 1, the range of disturbances highly influences the performance of a production system and its stability. So, an analysis of disturbances should always be the first step when considering the robustness of a production system. Herein, not only the crucial disturbances as observed in the past have to be considered, but also possible future disturbances against which a production system shall be robust.

4. Analysis of Robustness

As defined in section 2.7, this paper considers the robustness of a production system as its ability to remain working on a stable and high performance level despite the given risks. The existing risks are the disturbances the production system is exposed to. According to their definition, the disturbances are unintended and unwanted because of their negative effects on the system's performance. To increase the robustness of a production system the influence of the existing disturbances has to be reduced.

Therefore, actions can be chosen which either reduce the negative effects of disturbances or diminish their probability of occurrence. Both kinds of actions would have positive effects on a production system's performance level and stability. The particular effects of the different possible actions on a system's performance have to be analyzed in order to determine the system's robustness.

For measuring performance the KPIs have to be taken into account. Mostly, one KPI is not sufficient to describe the performance of a whole production system. Therefore, several KPIs need to be used and their correlations need to be taken into account. The chosen KPIs depend on the production system itself and the special interests of the user and lead to one aggregated performance indicator which builds the basis for the robustness analysis.

The value of the performance indicator depends on the disturbances and the given configuration of the production system and is thus equivalent to the target function value in chapter 2.1. The solution x corresponds to the system's configuration, which includes all machinery, equipment, staff, organizational processes, etc. in the production system. The influencing factors are represented by the disturbances. The configuration of a system can be changed by applying different actions.

In order to measure robustness according to the understanding of the term in this paper, the absolute values of the performance indicator and its deviation have to be regarded. So, at first the performance of the production system under different disturbances needs to be known. Therefore, the production system can be modelled, its behavior for certain disturbances can be simulated and its performance values can be measured.

Given the performance values, an integrated consideration of the absolute values and their deviation is carried out to find a solution with good performance values and little deviation. Therefore, the value-at-risk is chosen, because it rather focuses on the negative effects of an event. The standard deviation, for example, is insensitive for equally sized positive or negative deviations of the performance value. The idea of robustness however, is demanding for a good performance with little deviation. So, if a disturbance might cause an even better performance, this should not lead to a negative effect on the robustness of the regarded system's configuration. Besides, the value-at-risk allows including the individual risk aversion of the user. So, given the performance values for the regarded range Δu the value-at-risk for the performance can be calculated according to the given level of risk aversion. The retrieved value means: the performance will not drop below this value of the given risk-aversion. It will be called value-of-performance and is an indicator for the robustness of the regarded system's configuration.

However, the value-of-performance cannot be used to compare the robustness of different production systems, as the range of regarded disturbances, the chosen KPI and the level of risk aversion is chosen specifically for one production system. The value-of-performance can help to choose between different alternative configurations of a production system and to predict the effect of different actions on the system's performance.

Acknowledgements

This Research has been partially supported by the European Union 7th Framework Programme Project No: NMP 2013-609087, Shock-robust Design of Plants and their Supply Chain Networks (RobustPlaNet).

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