# System Dynamics Model of an Assembly System in Ramp-Up – Focusing Inspections

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This paper presents a System Dynamics (SD) model of an assembly system in ramp-up with special focus on inspections. The time in-between product development and stable series production is characterized by dynamically changing conditions referring to the product, processes and the assembly system's organization. Thus, SD serves as an excellent method to model the system's behavior within the ramp-up period. Based on a qualitative derivation of the system variables an explanation of their interconnection is conducted in order to be able to model the system quantitatively and thereafter to simulate effects which parametrical variations have on the superior ramp-up target *time to volume*. A special focus is set on the role of inspections as they verify the product quality which is a precondition for achieving an as short as possible time to volume. So far the analysis of inspections has not been in the focus of the existing research on ramp-up.

Keywords: production ramp-up, inspections, system dynamics, assembly system

## 1 Introduction

During the ramp-up of a production system (or more precisely an assembly system) changes and adaptions of the system are performed in order to reach the indicated peak production. Thus, the system shows a dynamic behavior over time (Jürging 2008; Gössinger and Lehner 2009; Gartzen 2012). The dynamics are on the one hand expressed by the continuous upgrading of the system referring to output and quality but on the other hand disturbances and unexpected changes of products and processes occur as the system is not in a stable state yet (Gartzen 2012). Due to diverse interconnections between the system's elements changes of one element cause variations of other elements as well.

Within this unstable system inspections take in a special role. They verify the product quality which is a precondition for generating more output. Especially in the early phases of the ramp-up inspections are necessary to get knowledge on the quality. During the progression of the ramp-up inspections may dynamically be adapted to the state of quality which should result in a reduction of the inspection intensity. However, as a consequence of occurring disturbances and unexpected changes a continuous decrease of the inspection intensity is not completely reasonable. Each disturbance or change of the system and its parameters may have an effect on the quality. As knowledge on this effect can only be obtained via an inspection a need for increasing the inspection intensity in this case occurs. It can be sub summarized that the inspection strategy in ramp-up is reactive, thus, depending on the system's behavior. However, inspections do influence the assembly system themselves. On the one side they have a not negligible impact on the output performance as they increase cycle or even takt times. On the other side inspections are designed as technical systems which themselves may be a source of disturbances to the assembly system.

The aim of this paper is to model the system's behavior with respect to its underlying target system and with special focus on the role of inspections. Therefore, it is necessary to analyze and explain the existing interconnections between the elements of an assembly system in ramp-up. System Dynamics (SD) is an appropriate method to conduct this modeling. SD helps to analyze the existing interconnections of the elements which describe the system and enables to quantitatively model the behavior over time. Thereafter different inspection strategies are tested in a scenario analysis in order to show that the inspection strategy has an effect on the ramp-up goals.

## 2 Characterization of the Ramp-Up

The phase between product development and peak production is characterized as the ramp-up (Terwiesch and Bohn 2001; Schuh, Stölze, and Straube 2008). During ramp-up the capacities of the production system are extended continuously with respect to quality issues in order to increase the system output until the indicated capacity (peak production) is reached. Within this phase dynamically adapted targets apply. The targets are set within the triangle of effectiveness (maximum output at maximal quality), efficiency (minimal effort) and time (minimal duration) (Lanza 2005, Winkler 2007). At the beginning of the ramp-up phase generating product quality through capable manufacturing processes (Garvin 1984) is singularly important. This importance declines over time, as soon as the indicated quality level is achieved. The focus is then set on enhancing the output performance, (Figure 1). Product quality is a precondition for raising the output. Only when both targets are achieved time objectives may be reached (Lanza 2005).

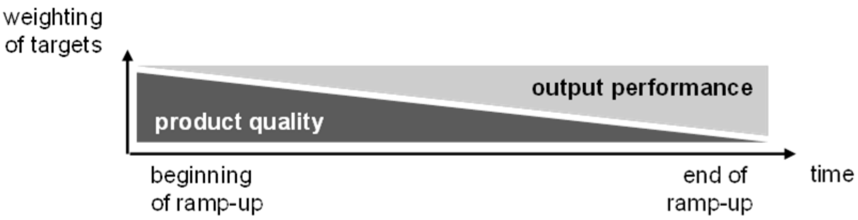


*Figure 1: weighted ramp-up targets*

Based on the underlying targets and conditions which apply to the ramp-up over time three ramp-up phases are distinguished, i.e. pre try-out serial, try-out serial and serial production start-up after the start of production (SOP) (Tücks 2010; Kuhn et al. 2002), (Figure 2). The pre try-out serial denotes the beginning of operating and qualifying the production equipment. Prototypes are produced under conditions closely related to real production settings. Series production tools are partly tested so that problems might be identified and processes improved. Within the pre try-out serial and try-out serial changes or modifications of the product and the processes are still an issue. Hence, uncertainties occur (Straub, Weidmann, and Baumeister 2006). During the try-out serial tools are already in full use and suppliers deliver their components under real production conditions (Schuh, Stölze, and Straube 2008). As soon as the assembly line is approved the serial production start-up begins at SOP with the job No. 1, which is the first product deliverable to the customer. Capacities are raised continuously and a stable production at peak production indicates the transition of the ramp-up into series production (Jürging 2008; Schuh, Stölze, and Straube 2008). (Gartzen 2012)

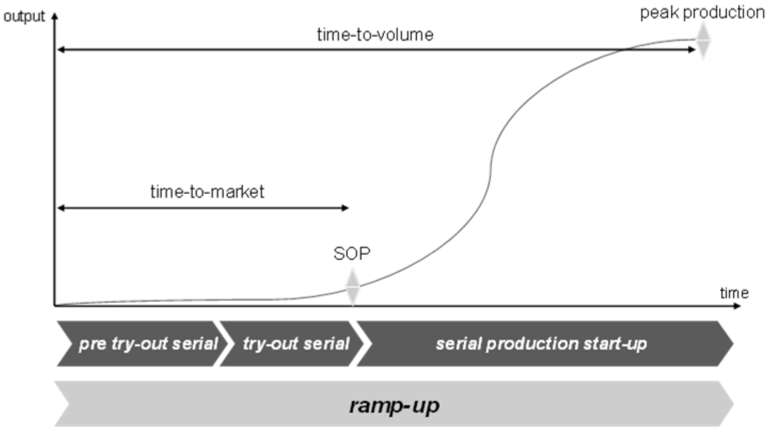


*Figure 2: Ramp-up*

## 3 Applying System Dynamics to Production Systems in Ramp-Up

### 3.1 Set-Up of the SD-Model

As System Dynamics serves in modelling and understanding the internal structure of a system that drives behavior, it is chosen to derive the model of an assembly system in ramp-up considering the above made conditions. The progress of the modelling is structured as follows:

- The system border and relevant system elements, which determine the observed system, are identified.

- The interconnections between the system elements are first derived qualitatively using Causal Loop Diagrams (CLD). (There is no explicit discussion of a stock-and-flow-structure in this paper as stock-and-flow-diagrams are only an interstage inbetween the qualitative and quantitative modelling.)

- A quantitative explanation of the interconnections and system variables is the basis for implementing the system’s structure into Vensim which thereafter allows to simulate the system’s behavior.

- A simulation of a demonstration scenario allows to test different inspection strategies and their effects on the system’s behavior and the rap-up targets.

For the purpose of addressing the problem statement of this paper, the system border is drawn around an in-company assembly system in ramp-up. Thus, the production network, suppliers and customers are not included into the system-theoretical model. The company which performs the ramp-up may only seldomly influence the production network and its actions. As a consequence of this and, furthermore, in order to reduce the model's complexity this in-company focus is chosen. The view on the in-company assembly system is an integrated one meaning that the ramp-up of the product as well as the ramp-up of the assembly processes and equipment are considered. In the scientific literature those two perspectives are often differentiated and treated isolated (e.g. Zeugträger 1998). An integrated view pays respect to the socio-technical definition of an assembly system, considering the product, processes and its organization.

In order to structurally and schematically define the relevant system elements an underlying framework of the system is set-up (Figure 3). It will further be referred to as the *ramp-up system*. It consists of a *ramp-up target system* and an *operational ramp-up system*. The behavior of the system is displayed in the operational ramp-up system. It results from the ramp-up system structure and parameters. The structure itself is defined by the system's constituting elements and their interconnections. The elements are characterized by parameters. A structural or parametrical variation affects the system behavior. Hence, knowing how the system behaves is valuable in order to configure the structure and parameters according to the targeted objectives of the ramp-up (Sterman 2000; Frank et al. 2009). Due to the special focus on inspections in this paper the operational ramp-up system explicitly considers factors which are able to map the impact of inspections on the system.

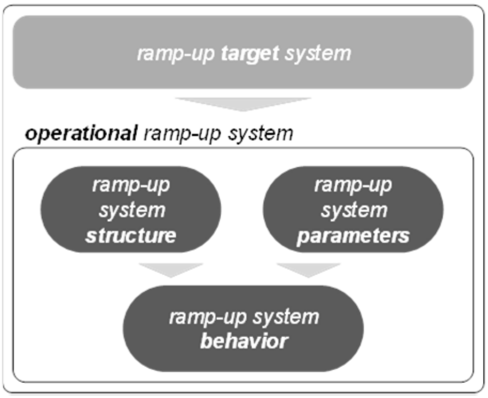


*Figure 3: Framework of the underlying ramp-up system (Frank et al. 2009)*

### 3.2 Ramp-Up Target System

The ramp-up target system is developed based on the existing state of the art (see section 2) within the triangle of time, effectiveness and efficiency. As effectiveness and efficiency are preconditions for achieving time objectives it is reasonable to choose a time variable as a superior target of the ramp-up The *time-to-volume* spans the timeframe from the beginning of the pre-try-out serial until reaching the peak production (Terwiesch, Bohn and Chea, 2001). Thus, the entire ramp-up period is covered. The time-to-volume, hence, is a suitable time variable to be looked at in ramp-up and may act as a superior target. The effectiveness of the ramp-up is represented by the product and process quality. Process quality is on the one hand the precondition for achieving product quality through stable and capable processes (*quality capability*), and on the other hand necessary for realizing the desired output performance (*output performance capability*) (Lanza 2005; Jürging 2008). The *expense of resources* is a variable referring to the efficiency within this paper's model (Ender 2009). The target system of the ramp-up is shown in Figure 4.

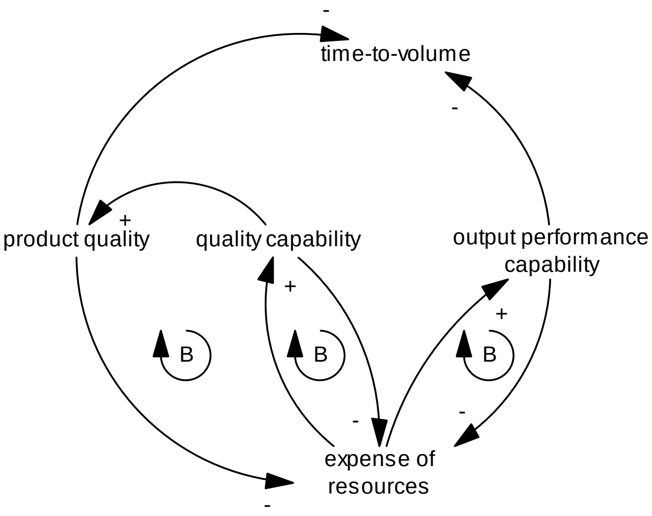


*Figure 4: Ramp-up target system*

Product quality and quality capability are part of a negative feedback loop with the expense of resources. Thus, it is possible to find a quality level at optimal cost. The same accounts for the balancing feedback loop between the expense of resources and the quality capability respectively output performance capability.

### 3.3 Operational Ramp-Up System

In order to derive the operational ramp-up system existing research works which define elements and interconnections within a production system in ramp-up are analyzed and adapted to fit this research paper's problem statement. System theoretical approaches are broadly used in literature to describe the ramp-up (e.g. Gartzen 2012, Heins 2010, Jürging 2008).

Gartzen identifies factors which drive or limit the complexity of an assembly system in ramp-up. He aligns those factors along the dimensions characterizing an assembly system which are product, process, network and organization. Except of the network dimension this classification fits to the above made framework definition. Gartzen discusses the factors' impact on the Overall Equipment Effectiveness (OEE). Although, he does not apply the System Dynamics method in order to analyze the existing interdependencies between the identified factors, the ramp-up's dynamic is considered by those factors. The structural procedure which Gartzen applies is used to derive the factors which are suitable for the System Dynamics model presented in this research paper. The factors Gartzen already identified are discussed against the background of this paper's problem statement. For this purpose other system theoretical research works on ramp-up are consulted.

The System Dynamics method itself has so far been applied to production systems in ramp-up by Heins and Jürging. Heins derives a qualitative System Dynamics model of factors facilitating the ramp-up of an assembly system using Causal Loop Diagrams. The author defines elements which are relevant for a ramp-up and matches them with 116 facilitating factors (Heins 2010, p. 62ff). The derivation of the facilitating factors is not conclusively justified. Nevertheless, the identified factors help to discuss the model. Jürging develops a modularized model of the ramp-up in the automotive industry. The system border is drawn around the production start-up phase, pre try-out serial and try-out serial are not regarded in the simulation model. The central module of the System Dynamics model is the production itself with the output as target variable. As the model is restricted to the phase after SOP rework takes in a central role in order to simulate the output. Rework, however, is not an issue within the pre try-out serial and try-out serial as the products are not delivered to the customer. Hence, Jürging's model is not able to simulate the complete ramp-up. The production module and, thus, the output is influenced by different factors which are defined in separate modules, namely *quality*, *product conformity*, *process conformity*, *disturbances of the production*, *worker development* and *detection of defects*. Jürging's model focuses extremely on the socio-technical aspect as a lot of the influencing factors are modeled via effects trying to simulate a worker's behavior. (Jürging 2008, p. 116ff) The factors Jürging uses to define his model of the production start-up give further indications for the derivation of the operational ramp-up system.

None of the above discussed research works (as well as other works on ramp-up not mentioned here) explicitly considers inspections in ramp-up. Thus, for the derivation of appropriate factors, which describe inspections and their impact on the system, relevant literature in the field of inspections is studied. A discussion of this literature will not be conducted in this paper in order to set the focus on the model itself. According to the framework definition and classification of the operational ramp-up system into the dimensions product, process and organization, inspections are aligned within the process dimension.

*Product dimension*

The relevant elements of a product which are used to set-up a SD-model of the ramp-up to address this paper's problem statement are:

- product variety
- product novelty
- producibility of the construction
- technical change of the product

The *product variety* results from a product's variety of parts, the technological product variety and the number of variants a product has (Gartzen 2012, p. 109f). A high product variety comes along with a high variety of the assembly processes which generate the products. Furthermore, the higher the variety of a product is the more complex this product is and the more likely it is that technical changes of the product have to be made during ramp-up.

The *product novelty* is defined by the degree of constructive-technological variance a product has compared with prior assembled products. The novelty of components, novelty of material and the novelty of the product structure affect the overall product novelty (Gartzen 2012, p. 110f). The novelty of the product has a huge impact on the novelty of the assembly processes as well as the inspection processes in ramp-up. Additionally, technical change of the product is an issue especially for new products as components, material and product structure are not completely tested yet.

The elements Gartzen uses to describe the product dimension are extended by the *producibility of the construction*. Referring to Jürging a lack in the producibility of the construction increases the probability of disturbances in the assembly process (Jürging 2008, p. 129).

Furthermore, *technical product changes* are implemented as a system variable into the operational ramp-up model. This is due to their relevance in ramp-up (among others Wangenheim 1998, p. 183; Fritsche 1998, p. 68; Terwiesch und Loch 1999, p. 160; Risse 2003, p. 27). A technical change of the product causes a technical change of the assembly processes, which produce that product, respectively of the inspection processes which verify the product's quality (Jürging 2008, p. 129). The processes have to be adapted to the changing conditions of the product.

*Process dimension*

The process dimension is divided into the assembly process and the inspection process so that the effects of and on inspections within the ramp-up system can be analyzed.

The assembly process is specified through the variables:

- variety of the assembly process
- novelty of the assembly process
- size of the assembly process
- degree of automation of the assembly process
- technical change of the assembly process
- technical progress of the assembly process
- disturbance of the assembly process

The *variety of the assembly process* results from the product variety. A high degree of heterogeneous processes used to assemble a product raises the system's complexity and the probability that disturbances of the assembly process occur (Gartzen 2012, p. 109).

The *novelty of the assembly process* refers to the novelty of the assembly equipment as well as to the novelty of the assembly procedure (Gustmann 1989, p. 41). As mentioned before, it arises among others from the product novelty and itself causes disturbances to the system.

The *size of the assembly process* is specified through the amount of assembly stations and the amount of assembly steps (Gartzen 2012, p. 116). The hugher the process the more process variables exist so that disturbances of the assembly process are more likely.

The *degree of automation* influences the output performance capability positively as shorter takt times enable higher production volumes. Furthermore, it is assumed that a high degree of automation forwards a high quality capability (Sommer 2008, p. 93). However, the higher the degree of automation is, the more complex an assembly system is as process variety rises.

A *technical change of the assembly process* has to be made when the product is changed, a disturbance of the assembly process occurs or when the indicated targets in the observed ramp-up period are not reached. Changes of the process might themselves cause new disturbances as long as the system is unstable. However, changes are in general made in order to implement a technical progress of the assembly and, thus, indirectly raise the quality capability or output performance capability. Nevertheless, each change is subject to monetary expenses and furthermore accompanied by a loss in the level of knowledge as prior learnt procedures and methods are not applicable any more.

The *technical progress of the assembly process* has positive effects on realizing ramp-up targets output performance capability and quality capability (Dyckhoff 2012, p 1442). Furthermore, the probability that disturbances occur is negatively influenced by a technical progress.

The drivers of *disturbances* are mentioned above. A disturbance may have two effects on the system, i.e. non-conformance regarding quality requirements or a break-down of the system so that no output is generated (Lanza 2005, p. 101). As a consequence of disturbances changes of the assembly process have to be made to suppress symptoms and root causes.

The inspection process is defined comparable to the assembly process via:

- variety of the inspection process
- novelty of the inspection process
- inspection intensity
- degree of automation of the inspection process
- technical change of the inspection process
- technical progress of the inspection process
- disturbance of the inspection process

Identically to the variety of the assembly process also the *variety of the inspection process* results from the product variety. The variety of the inspection process has an effect on the probability that disturbances of this process occur.

The *novelty of the inspection process* is defined through the novelty of the inspection equipment and the novelty of the inspection procedure applied. Comparable to the assembly process also the novelty of the inspection process arises from the product novelty. The higher the degree of novelty is the more probable disturbances to the system are.

The *inspection intensity* is the product of the inspection extend and the amount of inspection characteristics. The inspection intensity defines the knowledge on the product quality. Thus, this variable has extensive impacts on the ramp-up system. Based on a comparison of the inspected quality with the intended quality changes of the processes are conducted when the lack between the targeted and actual value exceeds predefined thresholds. The inspection intensity itself is influenced by changes of the assembly process and by a non-conforming product quality.

The *degree of automation of the inspection process* depends on the degree of automation of the assembly process in order to cope with the takt times the assembly process predetermines. The automation degree of the inspection process does not have an impact on the quality capability as inspections only verify the quality but do not generate it. Through a higher variety of the inspection processes caused by a higher degree of automation disturbances are indirectly more likely to occur (Gartzen 2012, p. 127).

A technical change of the product or disturbances of the inspection process are accounted as causes of *a technical change of the inspection process*. However, identically to the change of the assembly process a change of the inspection process also might cause new disturbances to the system. Contrarily, those changes might result in a technical progress of the inspection process. A technical change of the inspection process is always accompanied by monetary expenses.

A *technical progress of the inspection process* results from a change of the inspection process (Winchell 1996, p. 18). It influences the output performance capability positively to a distinct degree as, for example, takt times may be leveled with the takt times of the assembly processes. Additionally, the probability of disturbances of the inspection process is negatively affected through a technical progress.

A *disturbance of the inspection process* has an impact on the output performance capacity of the system (Gartzen 2012, p. 112) as generated products may not be tested and, thus, not released. There is no effect on the quality capability.

*Organization dimension*

The organization dimension respects the socio-technical aspect of the operational ramp-up system and organizational preconditions. Thus, it is characterized by the following factors:

- level of knowledge
- goodness of information

The *level of knowledge* describes the cumulated level of knowledge of the ramp-up personnel. It is dependent on the cumulated output during ramp-up and on changes to the system (Dyckhoff et al. 2012, p. 1441). The level of knowledge itself affects the output performance capacity and quality capacity positively.

The *goodness of information* is characterized by the quality of information and the information’s availability. Those factors are central organizational requirements for the ramp-up success (Gustmann 1989, p. 45; Heins 2010, p. 76). The relevant information helps to avoid or suppress disturbances.

Based on the above made derivation and explanation of existing interdependencies Causal Loop Diagrams are set-up modularly for each factor. One example is shown in Figure 5. As explained above, changes of the process might cause disturbances of the system. Those disturbances call for changing the system and its processes. Hence, those two system variables form a reinforcing feedback loop. However, a combination with the other modules may compensate this effect.

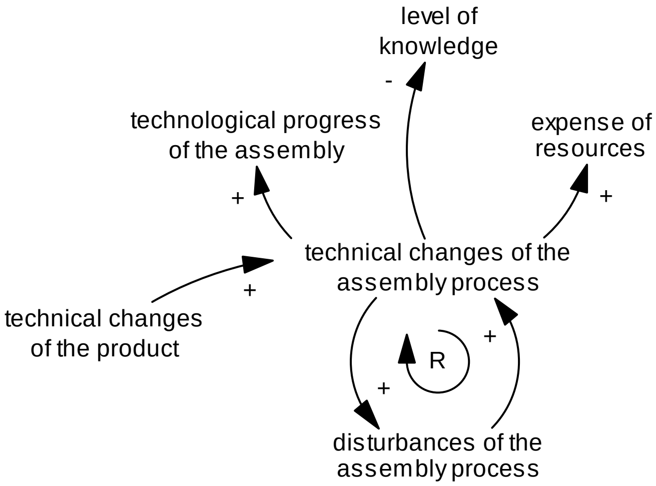


*Figure 5: Interdependencies of technical changes of the assembly process*

A combination of all CLD-modules and connection with the ramp-up target system reveals the interdependencies of the entire ramp-up system qualitatively. The structure is shown in Figure 6. Due to the high number of interconnections, each variable is part of numerous feedback loops. The quantitative SD-model, which is derived later in this paper and implemented into Vensim, shows that e.g. the ramp-up efficiency and effectiveness aims (i.e. quality capability, output performance capability and expense of resources) are part of more than 30,000 feedback loops. The inspection intensity, whose effects on the system's behavior are of special interest, is part of more than 23,000 loops. Due to this high number of feedback loops they are not marked in the qualitative SD-model shown in Figure 6.

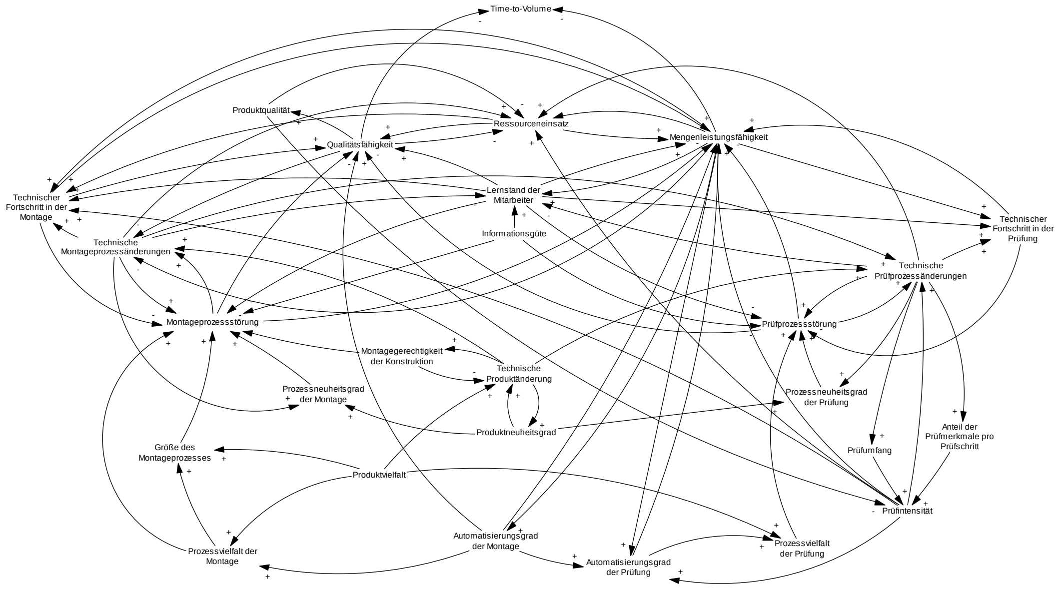


*Figure 6: Qualitative SD-model*

## 4 Quantitative SD-Model

The subsequent aim is to quantify the qualitative SD-model which is graphically expressed through CLDs. In order to be able to implement the model into Vensim a mathematical formulation of the system structure is given. The calculations are conducted with additionally inserted auxiliaries. The equations are described in written text. The source code is only given for some variables as an example in order to not overload this paper. Please, feel free to contact the authors for the whole source code.

*Quantification of the product dimension*

*Product variety* is formulated as an input variable with a value between 0 (no variety) and 1 (maximum variety). It is an estimator based on the product's variety of parts, the technological product variety and the number of product variants.

The *product novelty* declines linearly with the timely progress of the ramp-up when no changes of the product are made.

```
product novelty =
INTEG(
IF THEN ELSE(technical change of the product = 0,
 -MIN(0.01, product novelty),
MIN(effect product change product novelty, 1 – product novelty)))

---

Initial Value = Input
```

The *producibility of the construction* is a level variable with a value between 0 and 1, whereas 1 is an optimal producibility. It is positively influenced by a technical change of the product and reversely itself evokes the need to change the product. The initial value of this level variable is an input to the system.

```
producibility of the construction =
INTEG(MIN(MAX(
IF THEN ELSE(technical change of the product = 1,
  effect product change producibility,
0),
- producibility of the construction),
1 - producibility of the construction))
```

```
---
```

`Initial Value =` *Input*

*Technical change of the product* is modelled as a binary variable with value 1 in each period where a technical change occurs. The probability for a product change is the mathematical product of product variety, product novelty and (1-producibility of the construction).

*Quantification of the process dimension*

The *variety of the assembly process* is modelled as an auxiliary being the mathematical product of the product variety and the degree of automation of the assembly process.

In order to keep the model simple it is assumed that *the novelty of the assembly process* linearly depends on the product novelty. Similar to the product novelty, the process's novelty, thus, declines with the timely progress of the ramp-up. However, the novelty is additionally raised in case of a technical change of the assembly process.

```
novelty of the assembly process =
product novelty * factor novelty of the assembly process
+
MAX(
MIN(
 IF THEN ELSE(technical change of the assembly process=1,
   effect of change novelty of the assembly process,
 0),
 (1 - factor novelty of the assembly process * product novelty)),
- factor novelty of the assembly process * product novelty)
```

The *size of the assembly process* is the mathematical product of the number of work stations and assembly steps. In order to normalize the resulting value to the interval of 0 to 1, it is compared to a reference value.

The *degree of automation of the assembly process* serves as an input variable to the system. It is not considered as being constant, but increases stepwise each time a pre-defined level in output performance is reached. Those output levels are defined based on the planned set-up of the assembly line.

The *technical change of the assembly process* is modelled as a binary variable. It takes the value 1 every time a change of the assembly process is made in the observed period. The probability for a change to occur in a specific period depends on the following five factors:

- Referring to Jürging it is assumed that each technical change of the product calls for a technical change of the assembly process (Jürging 2008, p. 129).
- In case of a disturbance of the assembly process a change of the process is necessary.
- A variation of the degree of automation of the assembly process is – by definition – a change.
- In order to empower the ramp-up system, changes of the assembly processes are conducted. As one indicator for a needed modification the non-conformity of the current output performance capability with the targeted output performance capability is used. If the current output performance capability is too low a change is, however, only conducted with an assumed probability being equal to half of the difference between current and targeted output performance capability. If this difference is low, a change of the assembly process is less probable.
- The same procedure is applied in case the number of recognized defects of a product is larger than the permitted number of defects at this point in time. If the product quality is not conforming to the targeted product quality, a change of the assembly process is performed with an assumed probability of half of the difference of both values.

*Technical progress of the assembly process* is caused by a discrete event, i.e. a change of the assembly process. Hence, also the technical progress of the assembly process is modelled as a binary variable with value 1 in each period where a technical progress occurs. The probability of occurrence is dependent on several factors. On the one hand the probability declines with an increasing output performance capability or quality capability as it is increasingly difficult to further optimize the assembly process the closer it is to the targeted capability. However, on the other hand the probability positively depends on the cumulated output performance capability and, furthermore, on the applied resources which are needed to conduct the optimization. The level of knowledge and the inspection intensity are further indicatodrs. The probability of technical progress of the assembly system to occur is calculated considering all of the prior mentioned influencing factors.

```
technical progress of the assembly process =
IF THEN ELSE(technical change of the assembly process =1,
  RANDOM BINOMIAL(0, 1,
   ((1 – output performance capability) + (1 – quality capability) + average
cumulated output performance capability + cost factor change of the assembly
process /budget + level of knowledge + inspection intensity)/6,
  1, 0, 1, 0),
0)
```

A *disturbance* is also defined as a binary variable with value 1 in each period where a disturbance occurs. The probability of occurrence is determined by the *rate of disturbance of the assembly* which is added to the SD-model. This rate is comparable to the failure rate of a system used to calculate its reliability. In ramp-up it is assumed that this rate performs similar to the failure rate for early failures referring to the bathtub curve. It is mathematically modeled as an asymptotic decline function with the rate of disturbance at the beginning of the ramp-up being the initial value and the rate of disturbance during series production being the lower bound value. The slope of the asymptotic decline function is influenced by the process variety of the assembly, the process novelty of the assembly, the producibility of the construction, the level of knowledge and the size of the assembly process. The rate of disturbance of the assembly is furthermore reduced in the case a technical progress of the assembly exists. It is increased, though, when a change of the assembly system is conducted which does not result in technical progress.

Identically to the variety of the assembly process the *variety of the inspection process* is the product of the degree of automation of the inspection process and the product variety.

Similar to the novelty of the assembly process, the novelty of the inspection process is also assumed to be linearly dependent on the product novelty.

The *inspection intensity* is the mathematical product of the inspection extend and the amount of inspection characteristics. The inspection extend and the amount of inspection characteristics are defined based on the actual value of the inspected product quality and, thus, dynamically adapted (reduced or raised). However, in case of technical changes of the assembly process the inspection intensity has to be adapted. For this purpose a *change factor inspection* is introduced to the model.

```
inspection intensity =
INTEG(
IF THEN ELSE(technical change of the assembly process = 1,
  (1- inspection intensity) * change factor inspection,
 IF THEN ELSE((1 – product quality) * inspection intensity >
             (1 - "targeted product quality (t)" * tolerance factor quality),
   MIN("targeted product quality (t)" – product quality, 1 - inspection
intensity),
 -MIN(ABS(product quality - " targeted product quality (t)") * reduction
inspection intensity,
(inspection intensity - minimal inspection intensity)))))
---
Initial Value = initiale inspection intensity
```

The *degree of automation of the inspection process* is introduced to the model as an input variable based on the planned set-up of the assembly line.

Similar to the technical change of the assembly process the *technical change of the inspection process* is also defined as a binary variable. The occurrence of a change is affected by the following factors:

- A product change causes a change of the inspection process in order to be able to ensure an optimal inspection of the new product characteristics.
- Performing a change is furthermore a reaction on a disturbance of the inspection process so that this disturbance may be eliminated.
- A variation in the degree of automation of the inspection process is another indicator for a change of the inspection process.

*Technical progress of the inspection process* is introduced to the model as a binary variable. It depends on changes of the inspection progress which are considered as being discrete events as well. The probability of its occurrence is modelled identically to the probability of technical progress of the assembly process. It declines with an increasing output performance capability but is positively dependent on the cumulated output performance capability and the level of knowledge.

In order to include the *disturbance of the inspection process* in the model as a binary variable the *rate of disturbance of the inspection* is introduced to the SD-model. The definition of this rate is comparable to the rate of disturbance of the assembly with the difference that the function’s slope depends on the novelty of the inspection process, variety of the inspection process, inspection intensity and the level of knowledge. The rate is additionally reduced by technical progress of the inspection but increased when a change of the inspection process occurs which does not result in technical progress.

*Quantification of the organization dimension*

The *level of knowledge* is influenced by the cumulated output. No differentiation between conforming and non-conforming products is made as each assembled product comes along with a learning effect. In order to quantify this effect a factor is introduced, which is dependent on the so far existing level of knowledge and the indicated level of peak production. Additionally, the goodness of information has a positive a effect on the level of knowledge. However, the system variable is reduced by a change of the assembly or inspection process.

The *goodness of information* is simplified defined as an input to the system changing over time. The upper value is 1.

*Quantification of the ramp-up target system*

In this model, the *expense of resources* displays the ramp-up costs per period. The production costs of all conform and non-conform products, the inspection costs and the costs raised to conduct changes of the assembly respectively inspection processes represent the expense of resources. Costs for product changes are not included as they are added to the costs of product development.
In order to calculate the costs of technical changes of the assembly process the following scenario is set up: In each period a fixed budget for conducting changes exists. However, this budget is not always fully exploited. Through a ratio defining the importance of product quality and output performance in ramp-up a distribution of the budget between the quality capacity and output performance capacity is made. This ratio is calculated via the ratio of the targeted progression of those factors. Additionally, the deployed budget is dependent on the difference between the current and targeted value of the quality capability respectively output performance capability.
The costs for a technical change of the inspection process are expressed via a constant value.

An increase or decrease of the *quality capability* is simulated as being dependent upon the following relations:

- The ratio of the invested budget, which is used to conduct a change of the assembly process, is affecting the quality capability positively in case a technical progress of the assembly occurs. This monetary amount is multiplied by a monetary performance factor, which defines by what extend the quality capability can be raised with every monetary unit invested. Furthermore, the multiplication with the factor (1-quality capability) describes that the principle of a diminishing marginal utility also applies for the quality capability. The impact of the monetary expenses on the quality capability is a simplified approach as the real effects are hard to determine.

- A change of the level of knowledge or degree of automation of the assembly process influences the quality capability by another performance factor, also considering a diminishing marginal utility.
- In case of an occurring disturbance of the assembly process the quality capability is reduced by the performance factor multiplied with (1-quality capability). However, as not every disturbance affects the quality capability this influence underlies a certain probability.

The quality capability is the minimum of the *product quality* in each period as it is the indicator for the product quality which may be reached through stable and capable processes. However, the product quality might randomly also be generated through instable but capable processes. Thus, the product quality is calculated via a normally distributed probability mass function with mean quality capability and standard deviation (1 – quality capability).

```
product quality =
INTEG(MAX(
delta level of knowledge * performance factor quality capability * (1 -
quality capability)
+
IF THEN ELSE(disturbance of the assembly = 1,
  IF THEN ELSE(RANDOM BINOMIAL(0, 1, probability disturbance of the assembly
quality capability, 1, 0, 1, 0) = 1,
    - factor disturbance quality capability * (1 - quality capability),
    IF THEN ELSE(technical progress of the assembly process = 1,
      cost factor change of the assembly * ratio cost factor quality
capability * monetary performance factor quality capability *
(1 - quality capability),
    0)),
  IF THEN ELSE(technical progress of the assembly process = 1,
    cost factor change of the assembly * ratio cost factor quality capability
* monetary performance factor quality capability *
(1 - quality capability),
  0)),
-quality capability))

---

Initial Value = Input
```

In order to calculate the *output performance capability* two cases are distinguished, i.e. a breakdown of the assembly system occurs or not. A breakdown is the consequence of a disturbance of an assembly or inspection process affecting the output performance capability. However, the occurrence of a breakdown is subject to a certain probability. In case of a breakdown less units are produced in the observed period and the output performance capability is reduced by 30 percent of the previous value.

If no disturbance occurs within an observed period or if a disturbance does not cause a breakdown the output performance capability is calculated comparable to the quality capability:

- If a change leads to a technical progress of the assembly the ratio of the invested budget, which is used to conduct a change, is affecting the output performance capability positively. The monetary expenses are multiplied by a monetary performance factor, comparable to the quality capability, and the factor (1-output performance capability). The latter is used in order to take into account the principle of a diminishing marginal utility.
- A change of the level of knowledge or degree of automation of the assembly respectively the inspection process affects the output performance capability by another performance factor, again taking into account the diminishing marginal utility.
- As inspections take time the inspection intensity has an effect on the output performance capability to a distinct degree.

The *time-to-volume* is achieved as soon as the output of quality conform products reaches peak production at a stable level. The output of quality conform products is the mathematical product of the indicated peak production and the product quality.

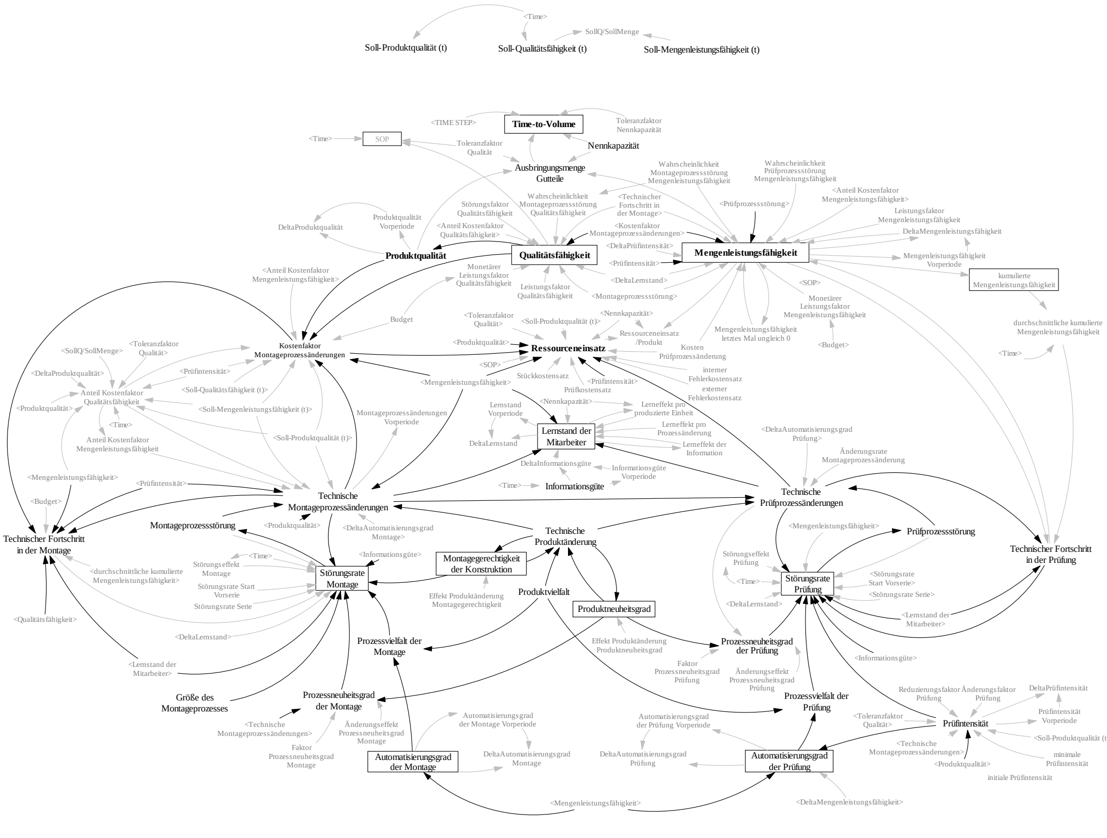


*Figure 7: SD-model implemented in Vensim.*

The derived structure of the ramp-up system helps to implement the SD-model into Vensim (Figure 7) and, thus, drive a simulation after parameterizing the system.

## 5 Simulation of a demonstration scenario

For purpose of a parametrization a demonstration scenario is set up, which is based on the data of a real ramp-up. However, not all factors' values (e.g. level of knowledge) are known as some are not being measured constantly during ramp-up. Especially the parameters of the auxiliaries which were additionally added to the system are unknown. In a first step the demonstration scenario is, thus, implemented into Vensim and the software's optimization function is used in order to define the parameters in that way that the output performance capability and quality capability of the simulated system are performing close to reality. The result is a parameterized system model. The simulated ramp-up goals of this system show a process close to reality. Hence, the model is used to simulate the effect of different inspection strategies on the ramp-up goals with special respect to the time-to-volume as superior goal. The observed timeframe consists of 225 days.

Six inspection strategies are tested on the model (see Table 1). Scenario III represents the inspection intensity which was derived from literature and is assumed to be the optimal strategy. Thus, the performance of this strategy compared to the other ones is of special interest. The courses of the scenarios are given in Figure 8.

*Table 1: Scenarios of the inspection strategy*

| | |
|---|---|
| scenario 0 | inspection intensity of the case study |
| scenario I | 100% inspection intensity during the whole ramp-up phase |
| scenario II | 0% inspection intensity during the whole ramp-up phase |
| scenario III | increasing the inspection intensity each time a change is conducted and dynamical adaption of the inspection intensity as a reaction on the product quality in each period |
| scenario IV | increasing the inspection intensity each time a change is conducted, but no dynamical adaption of the inspection intensity as a reaction on the product quality in each period |
| scenario V | dynamical adaption of the inspection intensity as a reaction on the product quality in each period, but no increase of the inspection intensity each time a change is conducted |

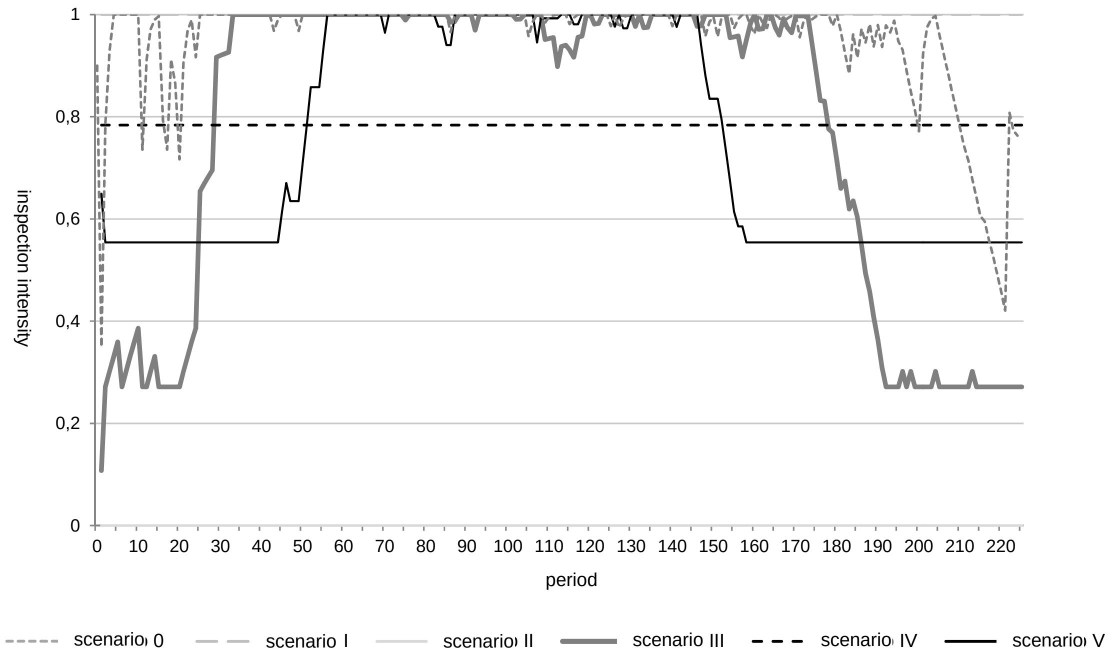
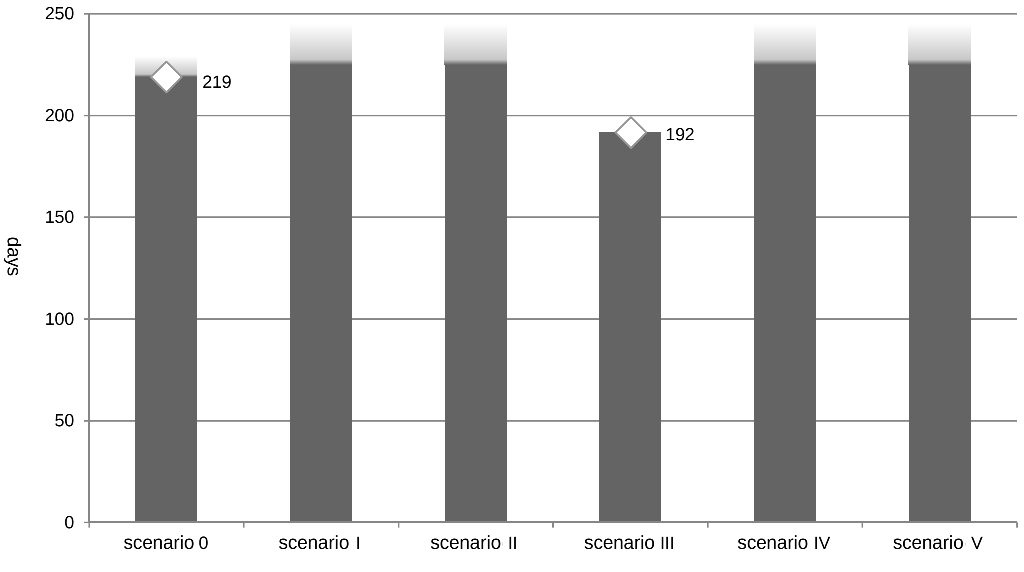


*Figure 8: Course of inspection intensity for different scenarios*

The simulation of the system behavior with these different inspection strategies reveals that indeed the inspection strategy has an effect on the achievement of objectives in ramp-up. As shown exemplarily in Figure 9 the duration of the time-to-volume is influenced by the inspection strategy. With scenario III, which is said to be the optimal strategy based on theory, the shortest time-to-volume (192 days) is achieved compared to the other scenarios. Scenario III is also superior referring to the ramp-up goals of efficiency and effectiveness.



# 6 Conclusion

In this research paper a system dynamics model of existing interconnections in an assembly system in ramp-up is developed in order to get knowledge on the system behavior. Within this model special focus is given to the role of inspections being the starting point of all quality improvement measures in ramp-up. The development of the model is based on an underlying framework consisting of a ramp-up target system and an operational ramp-up system. The prior comprises the five key target dimensions in ramp-up being product quality, quality capability, output performance capability, expense of resources and time-to-volume, which is acting as a superior target. The operational ramp-up system describes the system behavior as resulting from the system structure and system parameters. In order to determine the system structure, relevant system elements are derived describing the product, the processes (among them the inspection processes) and the organization. In a first step a qualitative modelling approach using Causal Loop Diagrams is used to represent the interconnections between the system elements. Thereafter, those interconnections are modelled quantitatively. The quantitative model is the basis for the implementation into the simulation software Vensim. Through a parametrization of the system's variables and auxiliaries a simulation of the system behavior is possible. A demonstration scenario is set up in order to be able to validate different inspection strategies and their effect on the ramp-up targets. With an inspection strategy reacting on changes of the system and conducting dynamical adaptions based on the product quality the best target values may be achieved. Prospective research activities may extend this approach and the developed model by focusing on a synthesis. The purpose of this synthesis is to define concrete and dynamically changing values for all system auxilaries which allow to implement an even more optimized inspection strategy with respect to the achievement of ramp-up targets.

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