Application of Resilience Analysis in Production Systems – Bombardier Transportation Case Study

Felicjan Rydzak, Edward Chlebus[1]
Centre for Advanced Manufacturing Technologies
Wroclaw University of Technology
ul. Lukasiewicza 5, 50-371 Wroclaw, Poland
Phone: +48 71 3204184 / Fax: +48 71 3280670
Email: felicjan.rydzak@pwr.wroc.pl, edward.chlebus@pwr.wroc.pl

Abstract: *This article presents the results of ongoing research on resilience in production systems. It refers to the term resilience as a way of dealing with uncertainty and disturbances. The proposed resilience analysis method, based on dynamic models, supports analysis of the production system in order to determine which structures and processes should be improved or reduced, and what resources preserved, in order to manage resilience. The application of the method is presented using results of the research project in Bombardier Transportation manufacturing plant in Poland. For the purpose of the analysis highly detailed discrete-event model and System Dynamics model were built. Both area of interest of both models complemented one another. In this paper the main focus is given to the System Dynamics model. In the course of the research project the System Dynamics approach proofed to be very useful for examining the impacts of various disturbances and possible solution policies. As a tool for the resilience analysis results dissemination, the dynamic model based simulator, was prepared.*

Key words: production system, operations management, resilience, dynamic models

1. Introduction

The developments in 18th and early 19th century in Great Britain, also known as the Industrial Revolution, began the process of economic transformation. Economies based on manual labour started to be replaced by one, dominated by industry. The application of water frame and later steam engines in cotton mills was the advent of '*factory systems*' – facilities specifically built to house machinery and bringing workers together (Farrar 1973).

Further improvements both in machinery and the production system organization enabled a significant increase in production capacity. Henry Maudslay, a British engineer, arranged in Portsmouth Block Mills a series of 45 woodworking, dedicated machines, powered by one 32-horse power steam engine, to produce wooden rigging

[1] Edward Chlebus is professor at Wroclaw University of Technology, head of Institute of Production Engineering and Automation and Centre for Advanced Manufacturing Technologies coordinator.

blocks (pulleys) for Royal Navy at Portsmouth. As the result, ten unskilled men replaced 110 skilled craftsmen. It was the first known production line in the world (Cantrell and Cookson 2002; Coad 2005).
About a hundred years later Ford Motor Company launched into the market the famous Model T – reliable, efficient and reasonably priced automobile (Rychter 1987). Henry Ford combined precision manufacturing, standardized and interchangeable parts, and division of labour. The introduction of the moving assembly line revolutionized production by significantly reducing assembly time and thus lowering costs (Ford and Crowther 2005).
The next transformation to the production systems was caused by the World War II. Mainly through the work of Toyota engineer Taiichi Ohno, the new production organization paradigm, called *Toyota Production System* (Ohno 1988)¸ and later known as *Lean Manufacturing* (Krafcik 1988; Womack, Jones, and Roos 1991), was developed. The scheduling of work started to be driven not by production targets but by actual sales. Elimination of 'wastes' in production system and application of quality improvement techniques enabled the company to produce relatively small lots of different vehicle models with little or no consequences in productivity or quality.

Throughout all the years of the production system development and transformations, and also today in the era of information technologies and computer aided operations in production systems (Chlebus 2000), the key challenge has remained unchanged – to virtuously manage strategic resources in the organization (e.g. people, machines and materials) and interactions between the resources, in order to accomplish the production system functions. What is the most suitable mix of the production system elements? What combination of the production system elements will secure the appropriate level of productivity and product quality? What and how changes and disturbances affecting the industrial organization can jeopardize the relations between the production system elements? What are the consequences of changes and disturbances over time to the output of the production system? These are only a few questions that have to be answered in any industrial enterprise at the operations management level. The common dilemma in that area concerns a day-to-day efficiency and a long-term performance (Beinhocker 2006). The strategic resources have to be managed in a way, that allows '*doing things right*' and '*doing right things*', which is the greatest challenge. For instance, one can take machines offline for maintenance, which will impair production capability today, in order to secure functionality and even better performance in the next months. The trade-off between '*now'* and '*tomorrow'* is even more profound considering all sorts of disturbances and uncertainties facing production systems along the whole chain of value adding processes.

This paper presents results of the research project on using dynamic models to analyse resilience in production systems as a way of dealing with uncertainty and disturbances. The paper delivers some findings from Bombardier Transportation manufacturing plant in Poland. It is organised as follows. In the next section an overview of resilience concept in production systems is presented. Section 3 discusses the method used to analyse the resilience. Section 4 introduces the investigated industrial enterprise, and the application of the resilience analysis with the main focus on the System Dynamics model application. The final section makes some closing remarks.

2. Resilience in Production Systems

Over the years in the production systems there could be observed an intensive head for performance results optimization. Industrial enterprises have tried to undo one another at cost cutting, process improvement, increased efficiency and productivity. The current production plants, often working in the distributed collaborative workspace, have become highly efficient structures. However, as Yourdon (2004) argue, the '*efficient'* systems are happed to be '*fragile'*, in the sense they are not *resilient* to disruptions of their normal operations. Furthermore, plenty of operations management techniques depend on assumption of stable and predictable environment. This assumption is a kind of utopia, considering all sorts of '*normal'*, '*abnormal'* and '*natural'* disturbances (Mitroff and Alpaslan 2003), which have a certain likelihood to impair day-to-day operations and very often the future, long term performance.

The arising question is how to operate in increasingly dynamic and changing environment facing more often and severe disturbances. The answer proposed in this paper is to analyse and develop resilience of certain functions in production systems towards various disturbances that may affect them.

The scientific term *resilience* was used for the first time in socio-ecological systems. This work refers to the meaning, originally proposed by Holling (1973) and further developed in the study of the dynamics of socio-ecological systems (Gunderson, Holling, and Light 1995; Walker et al. 2004), which emphasizes conditions of the system far from any stable steady-state, where instabilities can flip a system into another regime of behaviour, i.e., to another stability domain (Holling 1973). *Resilience* addresses the dynamics of dealing with disturbances – how a system absorbs the impacts of stress or shock and how it re-organizes afterwards. In that context *resilience* is defined as the capacity of the system to undergo disturbance and still maintain its functions, structures and controls. Three system characteristics broadly describe how to assess its resilience:

- the amount of change the system can undergo and still remain in the same configuration (retain the same controls on structure and function),
- the degree to which the system is capable of self-organization,
- and the degree to which the system can build the capacity to learn and adapt (Carpenter et al. 2001; Walker et al. 2002).

As Carpenter et al. (2001) argue further, it is crucial to specify what system state is being considered – *resilience of what*, and what perturbations are of interest – *resilience to what*.

Applying the above idea of resilience to socio-technical systems, the example of which is a production system, it can be assumed that the more resilient configuration of the production system is, the larger the extent and amount of certain disruptions the system can undergo without serious losses to the output, i.e. productivity, efficiency, product quality, etc. (Rydzak et al. 2006). In that sense, the resilience is highly attractive to any industrial organization, provided that the production system is in a desired/favourable configuration. The undesirable system configuration can also be resilient and make it difficult to regain the lost functions, structures and controls. Building resilience towards internal and external disturbances and changes enables the production system to sustain its functionality without serious losses once they occur.

Though the concept of resilience in production systems is becoming more and more popular (Horne 1997; Hamel and Välikangas 2003; Rice and Caniato 2003; Stoltz 2004; Christopher and Peck 2004; Sheffi 2005) it has not been clearly determined how to assess the resilience, however. There is a need for a method that would support analysis of the current state of the production system in order to determine which structures and processes should be improved or reduced, and what resources preserved, in order to manage resilience. This kind of analysis would identify what elements of production systems should be modified to lower resilience and facilitate transition of the production systems to a desirable configuration or otherwise increase resilience to make the production system remain in the desirable configuration.

3. Resilience Analysis Method

In this section a method of resilience analysis in production system is proposed. It is formalised into eight steps. The main element of the method is a dynamic model of the production system that is exposed to various disturbances scenarios. For that purpose continuous and discrete-event modelling and simulation approaches can be used. The framework of the method is described below and additionally depicted in Figure 1.

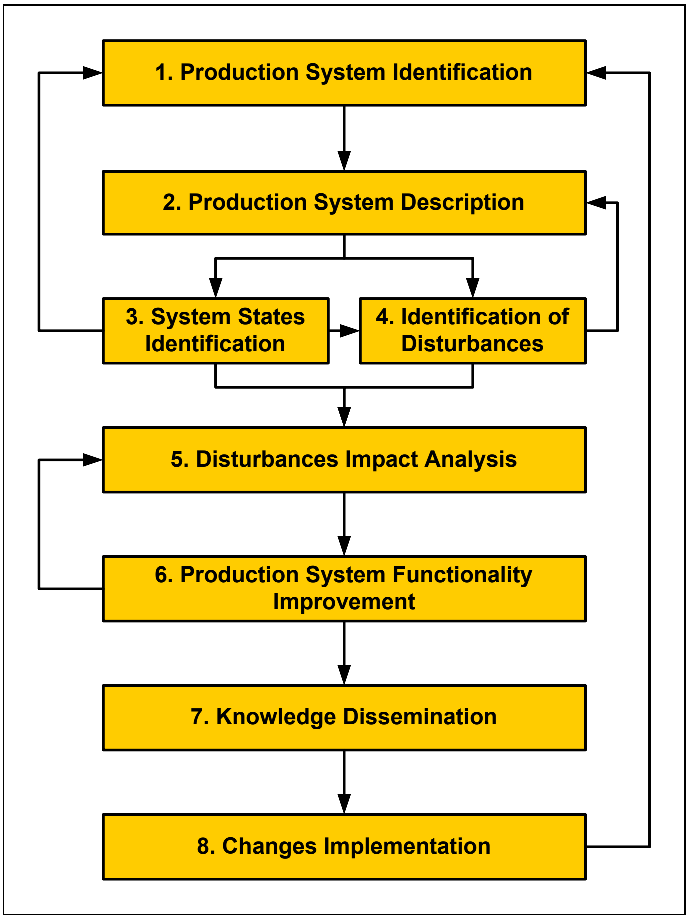

Figure 1 The framework of resilience analysis method in production systems.

Step 1 – Production System Identification

The first step in the resilience analysis method is the identification of the production system in terms of extensive and intensive boundaries that are to be covered by the dynamic model. At that stage **resources** (people, machines, materials, etc.), crucial **processes** (e.g. technological process, transportation operations), production organization **methods** (e.g. kanban, just-in-time) and specific **policies** (e.g. if machine A is broken all processing is conducted by machine B) are to be recognized.

Step 2 – Production System Description
During this step a dynamic model, representing the production system structure, is built. Both, continuous and discrete-event models can be used. However, in case of the discrete-event model the results should be considered over time.

Step 3 – System States Identification
At that point the current configuration of the system has to be determined (‘*resilience of **what** to what*’). System configuration is a collection of system state variables that meet certain set of criteria. Interactions between state variables determine the fulfilment of production system functions being a subject of the analysis. This step can make a modeller to add some structure to the dynamic model built in the previous step.

Step 4 – Disturbances Identification
Disturbance identification is an attempt to recognize various disturbances that may affect the specific production functions – ‘*resilience of what to **what***’. A set of various recognized disturbances constitutes a ‘disturbances scenario’. If required, the disturbances have to be represented in the model structure.

Step 5 – Disturbances Impact Analysis
Once the dynamic model is completed and covers all critical elements determining the defined function of interest as well as places of disturbances impact, the simulation experiments can be conducted. The influence of various disturbances, collected into the ‘disturbances scenarios’, is tested.

Step 6 – Production System Functionality Improvement
Explicit data on each model variable’s behaviour over time, gathered in the previous step, are investigated. The interrelations between production system elements are traced and analysed. In that way vulnerable places within the production system, which require a special attention or changes, are identified. Any changes are introduced to the dynamic model and the disturbances impact analysis is executed again. Usually, these actions are repeated until the production function, being a subject of the analysis, is maintained despite the impact of the defined disturbances.

Step 7 - Knowledge Dissemination
Usually, most understanding about the investigated problem remains within a small group of people, actively participating in the project. In order to share the results of the resilience analysis across the entire organization, a learning environment, based on the dynamic model, is built in form of a simulator. Using the simulator, everyone in the organization can experience the possible impact of disturbances on the production system.

Step 8 – Changes Implementation
The final step of the resilience analysis method is the implementation of proposed changes and improvements.

4. Application of Resilience Analysis

The application of the resilience analysis was conducted in a manufacturing plant of Bombardier Transportation in Wroclaw, Poland, within confines of the ‘Optimization of production process in Bogie Frames Division’ project (Rydzak, Chlebus, and Gajewski 2007).

4.1 Company Profile and Project Overview

Bombardier Transportation is a world-leading manufacturer of innovate transportations solutions, from regional aircraft and business jets to rail transportation equipment. Bombardier Inc. is a global corporation headquartered in Canada. The manufacturing plant in Wroclaw, Poland, a former Pafawag (Państwowa Fabryka Wagonów – National Railcars’ Factory), is a part of the Bombardier Transportation since May 2001. In the plant electric rail engines, railcars, as well as bogie frames for railcars and tramcars are produced. There are employed about 700 people. Most of the products are shipped abroad. Products manufactured in the Polish plant are used, among other, in Germany, Sweden, USA, Italy, Spain, Greece, China and Malaysia.

4.2 Project Overview

The main goal of the ‘Production process optimization in Bogie Frames Division’ project was to analyse a possibility of production orders fulfilment for two out of several currently produced products – bogie frame BR 185.2 and ICE, and the new, planned bogie frame – TALGO II HAST.

ICE and TALGO II HAST bogie frames are among the most important components of the super-fast trains operated in Germany and Spain, respectively (see Figure 2). The bogie frames usually go unnoticed but they are very important for safe railway operations, especially in the super-fast trains. For that reason a special care has to be taken during production operations regarding the products quality.

Figure 2 Super-fast trains – ICE (on the left) and TALGO (on the right).

The project was conducted in three stages:

1. Current situation analysis – collection and analysis of data on BR 185.2 and ICE products, regarding their construction, components, workstations layout, transportation routs, production resources (i.e. forklifts, cranes, fitters and welders), production and routing processes and components arrival cycles. All required information was gathered through observations, measurement and direct interviews on the shop floor and in technological, construction, production planning, and logistics departments.

2. *Future situation analysis* – the analysis focused on the new product (TALGO II HAST) concerning its construction, new dedicated workstations and those shared with ICE production process, transportation and production processes, planned production schedule and arrival cycles.
3. *Improvement of production orders fulfilment* – since the Polish manufacturing plant delivers its products for further assembly to another factory at the agreed dates, the objective of the production processes improvement is a sustainable and prompt order fulfilment over time. Based on data collected during the previous stages, the discrete-event and System Dynamics models were built and simulation experiments were conducted. The discrete-event model encompasses three investigated products, i.e. BR 185.2, ICE and TALGO II HAST, and their production processes. It covers technical aspects of the production process improvement (e.g. bottlenecks among production resources). The window of the discrete-event model, built using ProModel 2002, is presented in Figure 3.

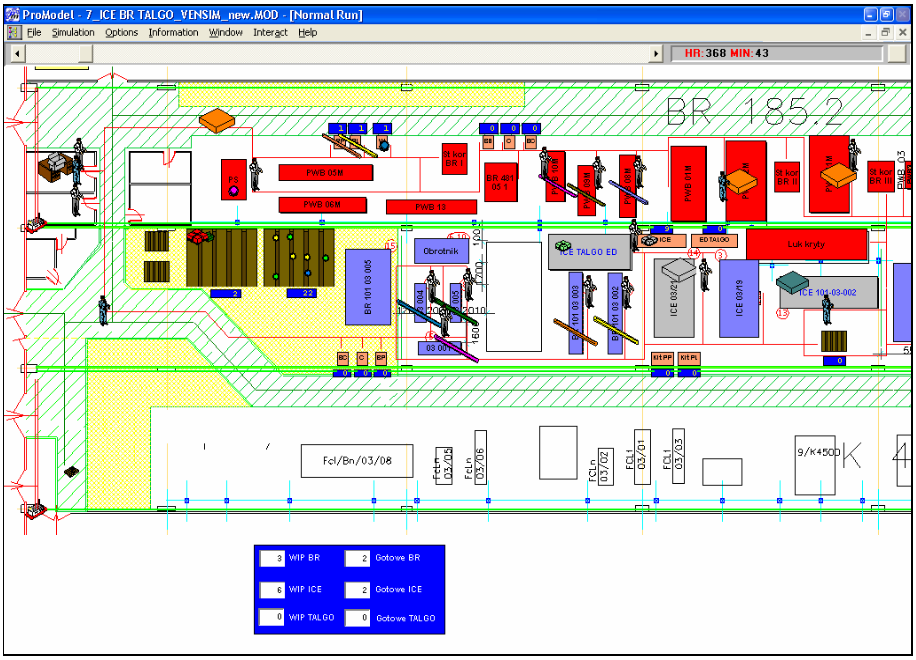

Figure 3 Discrete-event model in ProModel during simulation.

The System Dynamics model addresses operations management issues and policies (e.g. gaining experience by new employees in executing production tasks, the impact of behind schedule pressure on operations). It was decided that the System Dynamics model is to consider only ICE and the production start of the new bogie frame TALGO II HAST. It is planned that these two projects (separately from BR 185.2 bogie frame type) will share production space and some workstations. Also the same group of workers will conduct the production operations on them. The System Dynamics model uses some data from the discrete-event model (i.e. weekly arrival schedule and main bogie frame components availability). The overview of the System Dynamics model[2] is shown in Figure 4.

[2] Following the agreement with the company no detailed data on production processes, gathered during the research project, are disclosed. Thus the model equations are not presented in the paper. In case of any questions please contact the authors.

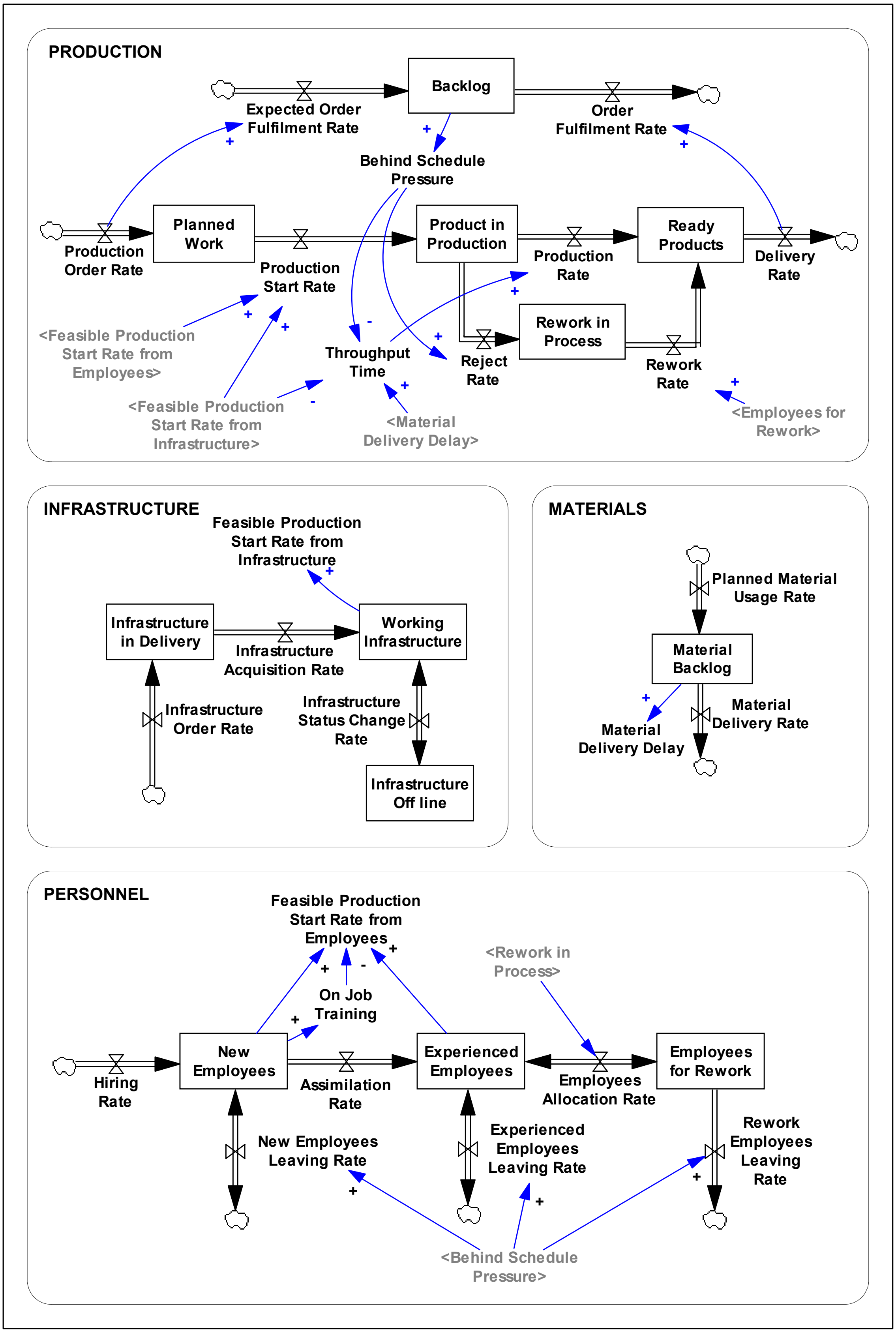

Figure 4 Overview of the System Dynamics model built for the purpose of the resilience analysis. The model consists of four interrelated sectors.

The dynamics of the System Dynamics model is driven by three main feedback loops – *Production Schedule Execution*, *Shortening Production Time*, and *Quality Erosion*.
The reinforcing **Production Schedule Execution** loop is responsible for fulfilling agreed production orders. The required number of bogie frames is started to be produced at the appropriate time (the *Production Start Rate* is constrained by the *Feasible Production Start Rate from Infrastructure* and *Feasible Production Start Rate from Employees*). The *Production Rate* is adding to *Ready Products*, which are delivered (at *Delivery Rate*) for further assembly to another factory. On time delivery reduces *Backlog* and thus *Behind Schedule Pressure*. Products of high quality do not require any rework operations so workers are freed to execute the production schedule further.
In case of any *Backlog* the **Shortening Production Time** balancing loop is activated. If there are any unfulfilled orders the *Behind Schedule Pressure* arises. The employees are forced to work faster, cutting down *Throughput Time*, increasing the *Production Rate*. As a result more *Ready Products* are delivered to the clients and the *Backlog* in reduced.
On the other hand the *Behind Schedule Pressure* turns on the **Quality Erosion** balancing loop. The employees under the pressure make more mistakes increasing the *Reject Rate*. If there are any bogie frames to be corrected (*Rework in Process*) the *Experienced Employess* are allocated to rework operation. The products are ready for delivery with the delay (additional time required to correct the defective bogie frames). The corrected bogie frames delivery decreases the *Backlog*.
In some cases the *Behind Schedule Pressure* can lead to the situation when the pressed workers forget about health and safety issues. Due to any accidents the number of available employees can be temporarily impaired.
Another important structure of the System Dynamics model is the employment of the new workers. They require on the job training which drives the Experience Employees from the production tasks, decreasing at the same time *Feasible Production Start Rate from Employees*.
Feasible Production Start Rate from Infrastructure is determined by the Working Infrastructure. The new machines/workstations can be purchased but there is the infrastructure acquisition delay. Additionally, the machines can be temporarily unavailable due to breakdowns.
Any *Material Delivery Delay* extends the bogie frames *Throughput Time*.

4.3 The Resilience Analysis

The project stages described in the previous sub-section reflect steps of the resilience analysis method. Once the main elements of the production system were identified (*Step 1 – Production System Identification*), i.e. products, production resources, production and routing processes, arrival cycles, etc., the computer simulation models were built (*Step 2 – Production System Description*). Discrete-event model is a highly detailed representation of the production processes whereas the System Dynamics model tries to capture 'hard' and 'soft' issues of the production system required for dynamic changes and policy options analysis. In this paper most attention will be given to the System Dynamics model. As to the *Step 3* of the method, *System States Identification*, the system was considered to be in a favourable configuration and the production function of interest – sustainable and prompt order fulfilment over time – has been successfully accomplished by the time of the project realization. The production start of the new product, TALGO II HAST, is considered here as the disturbance (*Step 4 – Disturbances Identification*). Later, other disturbances could also be tested, for instance machines breakdowns, employees leave or materials unavailability. However, the sustainable production of the three investigated products was at the most importance for the company. As to the next steps of the resilience analysis method, they will be presented more precisely in this sub-section.

Step 5 – Disturbances Impact Analysis
Based on the computer simulation models the impact of the new product introduction was investigated. Figure 5 illustrates results of the discrete-event model simulation, namely the impact of the new product production start on the throughput time of all considered products, at the final stage of the bogie frames production (i.e. bogie frames assembly). For each bogie frame, planned to be started at the certain point in time (Production Schedule Time), the throughput time was calculated as a time from starting fitting together the ready bogie frame components until the final product quality control. Since the production operations on the bogie frames takes a significant amount of time the throughput time was expressed in working days.

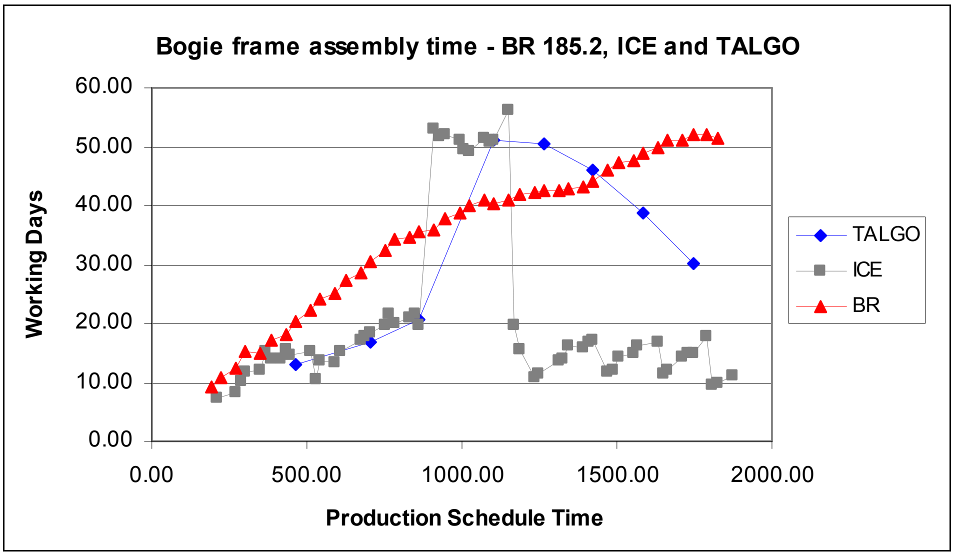

Figure 5 Bogies frames assembly time changes after TALGO II HAST production start.

The extended throughput time is the result of the increased number of work-in-progress – there are more bogie frames and bogie frame components to be processed in the considered production system. Additionally, some of the bogie frames and their components share the same production resources. If the production resources are not available to serve the entities, they have to wait to be processes and the throughput time extends. This problem is experienced soon after the production of TALGO II HAST is started, leading to blocked workstations around time 800 hours of the simulation scenario. For the purpose of the new product production start impact illustration only an excerpt of the planned production schedule is simulated and presented in Figure 5. Thanks to decrease in the number of processed bogie frames components, due to delayed but successive production schedule fulfilment, production resources are freed to serve awaiting entities (well visible around time 1200 of the simulation scenario). The extended simulation scenario covering a long-term production schedule, results in situation when the throughput time is maintained at the great value. However, even in case of the scenario dealing only with the production schedule excerpt it is evident that for the given production resources, technological process and arrival cycles, the introduction of the new product to production would prevent the sustainable and prompt order fulfilment over time.

Step 6 – Production System Functionality Improvement

Discrete-event model

The computer simulation of the discrete-event model, used during the project, allowed for identification of the bottlenecks in the production system. It was realised through three stages: 1. elimination of stoppages in production processes caused by production resources unavailability; 2. identification of blocked workstations and adding additional workstations further up production process if required; 3. adjustment of production resources (mainly fitters and welders) for the optimal fulfilment of the determined production function. Based on that analysis the requirements for specific kinds and amount of additional workstations and production resources (i.e. fitters and welders) were recognised (*note*: since the main focus of this paper is the System Dynamics model, more detailed analysis based on the discrete-event model are not presented).

System Dynamics model

Though very useful on the technical level, the discrete-event model simulation failed to deliver more insights into the operational area, however. It does not cover certain delays (e.g. new employees assimilation time) and 'soft' factors, inherently embedded into the production system (e.g. behind schedule pressure influencing cycle time). For such aspects the System Dynamics model was used.

Simulation 1 scenario

As far as the System Dynamics model is concerned, Figure 6 compares results of two simulation scenarios for *Production Order Rate* and *Ready Products*. The Base Run scenario considers production of the ICE bogie frame alone, and Simulation 1 scenario covers production of the ICE and the new product - TALGO II HAST. The time 0 indicates the beginning of the production schedule for both products, prepared by the production planning department (again, only an excerpt of the long-term production schedule is presented here).

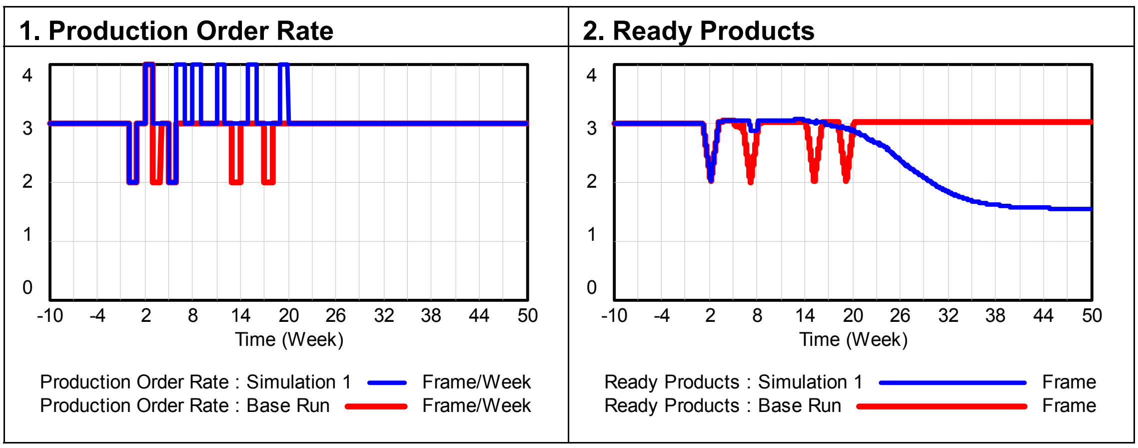

Figure 6 Results of the System Dynamics model simulation showing impact of the new product production start.

The average production rate of the ICE product, as well as ready products delivery rate for further assembly, are rarely greater than 3 bogie frames per week. As illustrated above (Figure 6, red line) the current system structure (i.e. available production resources, infrastructure, production methods, and internal production policies) enables the proposed ICE production schedule fulfilment. Products are ready to be shipped at the required points of time to clients (Figure 6, graph #2, red line). However, in case of production of two products – ICE and TALGO II HAST (Figure 6, blue line), the production function i.e. sustainable and prompt order fulfilment over time, is impaired. As a consequence of certain problems in the production systems there are not enough ready products to be delivered for further assembly - the average number of Ready Products fall below 2 frames (Figure 6, graph #2, blue line). In reality, the production plant would be charged fees for the late deliveries. From the perspective of the resilience analysis, the production system was not resilient enough and in face of the specified disturbance it moved to another, unfavourable stability domain.

Tracing the behaviour of the System Dynamics model variables and analysing interrelations between the production system elements, the root causes of the problem will be identified. The production functionality improvement will concentrate on identification of structures and processes that should be foster or reduced, and what resources have to be preserved or acquired, to make the production system face the defined disturbance without serious losses in the functionality.

There are two potential constraints in the considered production system – the availability of *production infrastructure* and *personnel* (i.e. fitters and welders).The infrastructure and employees have a great impact on the production function fulfilment.

The *Feasible Production Start Rate from Infrastructure* (Figure 7, graph #1) and *Feasible Production Start Rate from Employees* (Figure 7, graph #2) are slightly above a value of 3 bogie frames per week. Over time the availability of infrastructure remain constant (the scenario does not consider any machines breakdowns) whereas the *Feasible Production Start Rate from Employees* decreases, only to reach a highly unsatisfactory level of about one and half bogie frame per week. These two factors constrain the scheduled production start rate (scheduled products, but not started yet, accumulate as *Planned Work* – Figure 7, graph #3) and also influence the number of *Products in Production* (Figure 7, graph #4).

The number of *Products in Production* is additionally influenced by the effect of the internal pressure in the organization arising from the *Backlog* – a discrepancy between expected and actual order fulfilment rate (Figure 7, graph #5). The *Behind Schedule Pressure* shortens the production *Cycle Time* (Figure 7, graph #6) so that the bogie frame production is completed faster. Unfortunately, the employees working faster make more mistakes, execute the operations less precisely or just omit some of them on purpose. Since the bogie frames are very important elements of the railcars responsible for safety and ensuring good ride comfort, they undergo a thorough quality control. Most of defects and shortcomings are identified (through 3D coordinate measuring, RTG and ultrasound examinations) and the faulty bogie frames have to be reworked (Figure 7, graph #7). In order to execute rework operations, employees are allocated from production to rework tasks (Figure 7, graph #8). In some cases the *Behind Schedule Pressure* can also jeopardise safety issues in the organization. A fraction of employees taking a sick leave decreases the *Feasible Production Start Rate from Employees* even more.

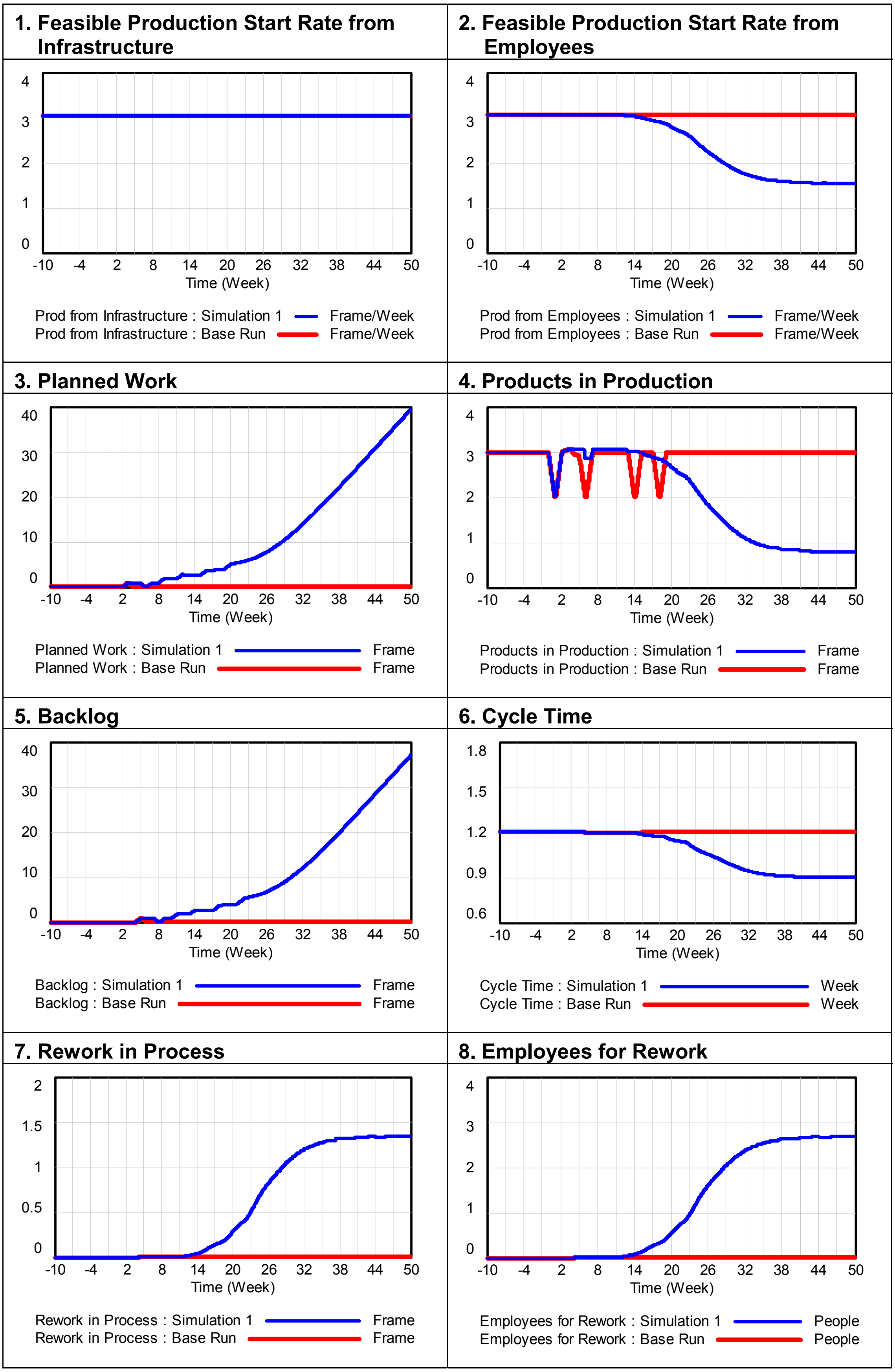

Figure 7 Results of the Simulation 1 compared to the Base Run scenario.

Simulation 2 scenario

The behind schedule pressure arises as a consequence of the focus on the '*cost world*' (Goldratt 1997), whereas identification of the constraints is rooted in the '*throughput world*'. If the behind schedule pressure was abandoned (as in the Simulation 2 scenario), the planed production schedule would not be completed on time but the functionality of the considered production system would not shift to the highly undesired configuration. There would be no pressure to cut down cycle time leading to mistakes and defects. Thus, the rework operations would remain on the minimal level (Figure 8, graph #1), and employees would be saved for production operations (Figure 8, graph #2). The production of ICE and TALGO II HAST bogie frames would be realised at the maximum possible steady rate, determined by feasible production rate from infrastructure and employees (Figure 8, graph #3). Any arising *Backlog* would be, if possible, consequently reduced over time (Figure 8, graph #4).

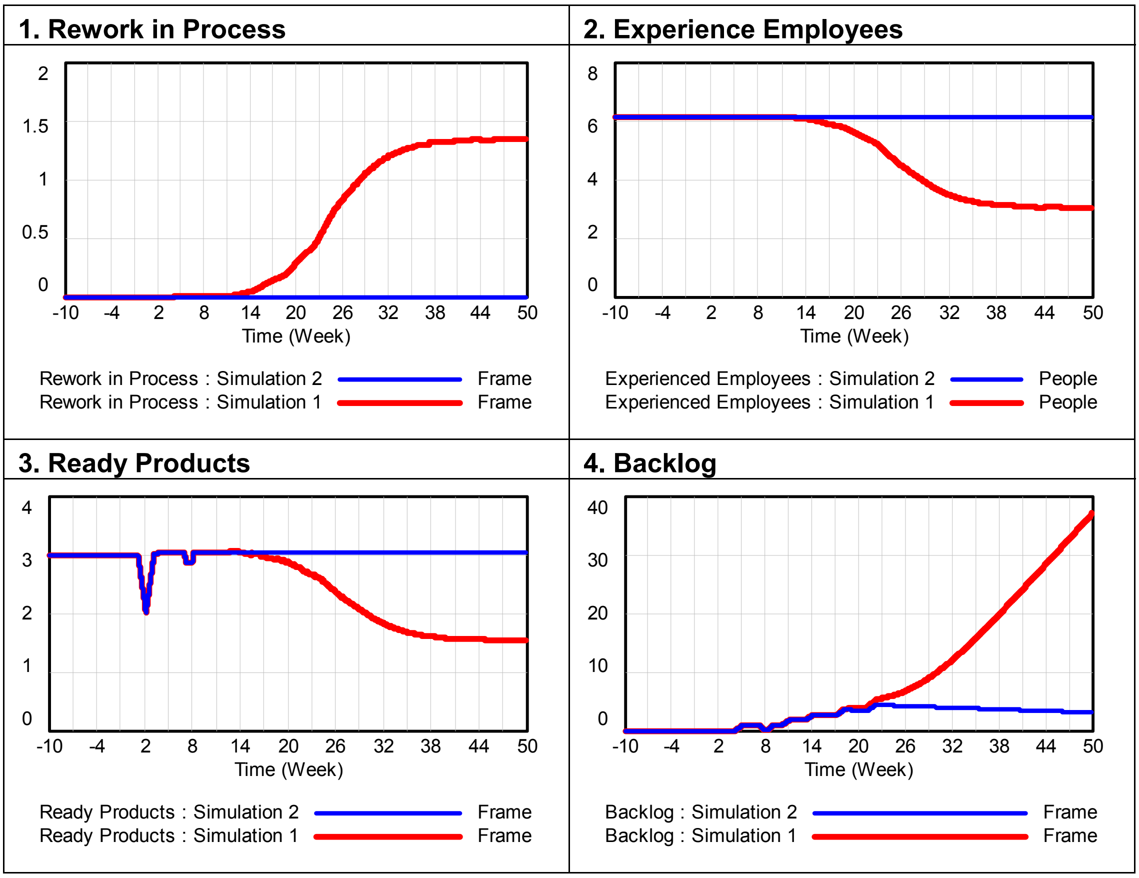

Figure 8 Results of the Simulation 2 scenario (compared to Simulation 1 scenario output).

Simulation 3 scenario

In order to improve the considered production function fulfilment, new production resources have to be acquired. The Simulation 3 scenario illustrates a case of two machines installation and four additional workers employment (the behind schedule pressure is active). The machines delivery takes 12 weeks. Once delivered, the *Feasible Production Start Rate from Infrastructure* is improved (Figure 9, graph#1). As far as new workers are concerned, at the moment of the employment the *Feasible Production Start Rate from Employees* drops down. The reason for that is that the *Experienced*

Employees have to deliver on-the-job training for *New Employees*. The assimilation takes about 2 months. If the enterprise decides to invest in the new employees initially, in the long term period it is able to improve its production output, which is a 'worse before better' situation (Figure 9, graph#2). The resulting *Production Start Rate* (Figure 9, graph#3) leads to some *Backlog* (Figure 9, graph#4), which is considerably smaller compared to the Simulation 1 scenario (Figure 7, graph #5), however.

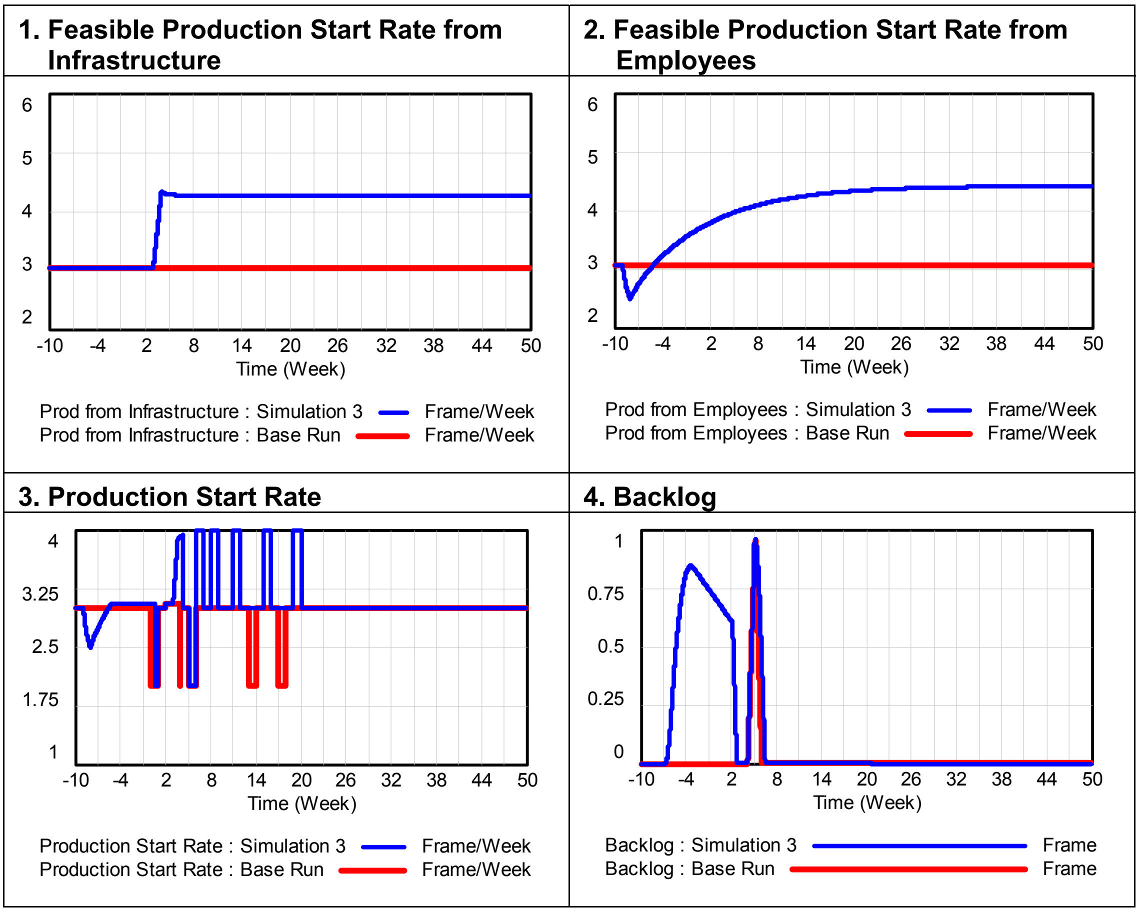

Figure 9 Results of the Simulation 3 scenario (compared to Base Run scenario output).

Based on the above discrete-event model simulation and System Dynamics simulation scenarios results, it is recommended to acquire all necessary resources well in advance to secure sustainable and prompt order fulfilment over time. Additionally, new employees could be hired at lower rate for a longer period of time in order to mitigate the impact of on-the-job training on the availability of experienced employees for production. Furthermore, more consideration should be given to the long term performance. Too much focus on the day-to-day performance indicators, rooted in the 'cost world', may lead to highly undesirable consequences.

Step 7 and 8 - Knowledge Dissemination and Changes Implementation

For the purpose of the resilience analysis findings and results dissemination, a simple interactive learning simulator was prepared – Production System Simulator. The window of the simulator is presented in Figure 10. It is based on the System Dynamics model used in the resilience analysis. Users, delivered with the Graphical User

Interface, can make some changes to certain parameters and observe the dynamics of the production system in four areas – *Production*, *Personnel*, *Infrastructure* and *Materials*. More sophisticated parameters are available in the *Advanced* section. Such a simple application can be spread across the entire organization making every employee experience the potential problems on their own. Apart from the TALGO II HAST production start, users can construct their own disturbance scenario (for instance increase mean time between machines failures, decrease productivity of experienced employees, change production cycle time, etc.) Acquainted with the problems and the possible solutions it is highly possible that the users of the simulator would be more engaged and willing to implement changes proposed in the aftermath of the resilience analysis. The exercises with the simulator can stimulate a process of building resilience of the current production system configuration or shorten the transition process from the current system state to the desired conditions.

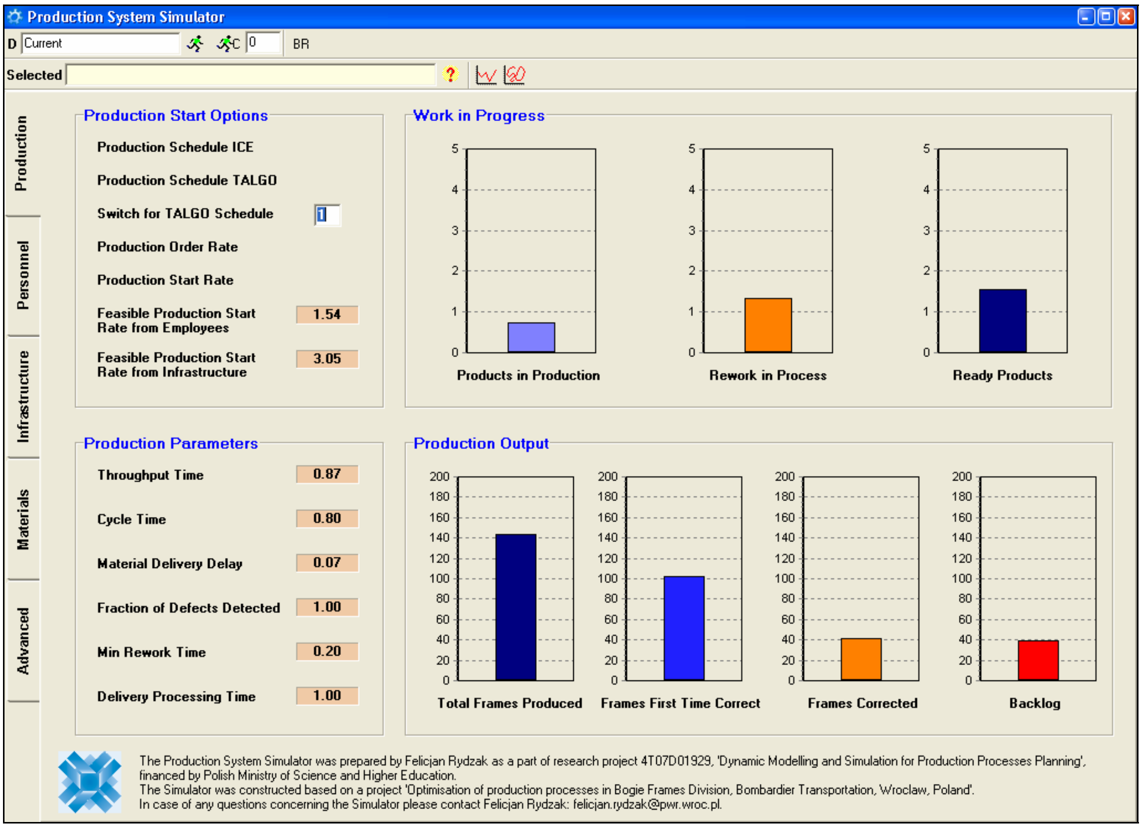

Figure 10 The window of the Production System Simulator.

5. Conclusion

The overview of the research project in Bombardier Transportation presented in this paper illustrates a successful application of the proposed resilience analysis method to the real problem in production system. In the course of the analysis it was determined what policies should be reduced, and what resources acquired, in order to improve resilience of the favourable system configuration. It was demonstrated that the excessive focus on a short-term performance indicators in face of disturbances can jeopardise the production function fulfilment over a longer period. Furthermore, it is often unavoidable to experience lower performance 'today' in order to secure superior results in the future.

Both models used for the resilience analysis, discrete-event and System Dynamics, complemented one another. The model built using ProModel delivered thorough technical results whereas the application of System Dynamics was dedicated to operations management issues. As far as the example of personnel employment is concerned, the technical results specify the required number and roles of new employees (e.g. fitters or welders) while operational issues focus on employment and on-the-job training policies. The great advantage of the System Dynamics model is its 'transparent' structure, which can be discussed with all parties involved. During the simulation experiment the behaviour of each model variable as well as interrelations between variables can be easily traced over time and analysed.
Computer models used in the resilience analysis encompass quite vast area of production system (production resources, processes, methods and policies) and the method itself is quite complex. For that reasons, the recommendations regarding functionality improvement do not have to be obvious at first sight. Thus, very important step of the proposed analysis is knowledge dissemination across the organization. Even a simple simulator, giving the opportunity to experience the impact of disturbances and explore potential solutions, can stimulate learning in organization, and make it move to desirable configuration or otherwise build resilience to remain in the favourable conditions, though the impact of the real disturbances.

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