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SIMULATIONS OF PRODUCTION-DELIVERY MODELS USING CONVENTIONAL METHODS OF DYNAMIC SYSTEMS: ZELGRAF COMPANY AS A CASE STUDY

The article presents the subsequent steps in developing a simulation model of the production-delivery system in a manufacturing company. Initially, the essence of the production-delivery process, namely all key processes that constitute the core business of a manufacturing company was explained. The most important decision principles directly related to these processes were identified and briefly characterized. This was followed by a presentation of the business profile of Zelgraf manufacturing company, where tests aimed at a practical understanding of the processes were carried out. This knowledge was useful in selecting variables of the mental model related to production-delivery processes, which are presented in tabular forms. The variables of the mental model, linked in a cause-effect diagram formed the basis for designing the simulation model. A target simulation model was developed relying on the cause-effect relationship diagram. This involved the application of the method of dynamic systems. The Vensim® DSS software was made use of both in designing the model and simulation. The different definitions of variables and the constant values for the model were provided using the programming language. These values were the direct outcome of empirical studies conducted in a given company. This was followed by the validation of the simulation model based on three methods. The last stage involved conducting a simulation of the model for an adopted stage, the presentation of the path of the accumulatory variables, including chosen variables of the system and finally an analysis of the results obtained was conducted. Possible practical applications of the designed model were mentioned in the conclusion.

Keywords: production, delivery, simulation modeling, system dynamics

1. INTRODUCTION

Modelling ought to be understood as an experimental or mathematical methodology for studying complex systems, phenomena and processes be they technical, physical, chemical, economic or social, relying on the construction of models. The main purpose of modelling using the methods of dynamic systems is to graphically illustrate the structure of a given system, its complexity and interdependence, and also seek possible solutions to difficulties that therein exist. Experiments conducted using models developed in the virtual world are useful in designing a real (perceived) world, while experience gained in the real world do provide information about the virtual world.

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The objective of the paper is to present a simulation model of the production – delivery system developed by Zelgraf company. The model was developed using the conventional methods of dynamic systems[3]. Thus the company is able to conduct series of tests and strategies associated with processes of production and sales. The model embodies key physical and information flows, along with the decision patterns that govern it. The necessary empirical data for the model, namely the various variables and constants as well as the constant values were obtained from the company in study. The research was in the form of in-depth interviews with the company's management, observation of production and delivery processes as well as the analysis of resource materials.

2. PRODUCTION AND DELIVERY AS KEY PROCESSES OF A COMPANY'S CORE BUSINESS ACTIVITY

One of the most important activities, amongst others, that is evident in every company is its core business activity. The primary activity of a production company can be defined as a series of steps necessary for the production of goods, which are the items of sales and constitutes sources of incomes to finance costs of operations and development of the given company.

A basic element determining the core business is choice of what to produce, how and for whom, which often involves a definite determination of the inventory profile and size of operations. Having agreed on these, then comes the conceptional design of the intended activity (also known as preparation of production), the assurance of appropriate processing materials for future production, production equipment as well as manpower. The next stage is the organization of production along with ensuring the economic rationality of production processes being implemented, including the assurance of its proper execution[4].

Production can, thus, be defined as a set of interrelated and mutually conditioned work processes that constitute a whole in course of which people, using the goods and forces of nature produce material objects, which serve as utilitarian goods to meet man's social needs. The fact that production processes occur in variety of forms hinders its typology.

The next core process in an industry that is directly associated with production is the delivery of manufactured products. The most important task of the delivery unit in a company is the timely supply of finished goods to the customers. Besides, the delivery employees are engaged in the following tasks[5].

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[3] J. Forrester, *Industrial Dynamics,* MIT Press, Cambridge 1961; E. Kasperska, *Dynamika systemowa. Symulacja i optymalizacja,* Wydawnictwo Politechniki Śląskiej, Gliwice 2005; R. Łukaszewicz, *Dynamika systemów zarządzania,* PWN, Warszawa 1975; A. Piekarczyk, K. Zimniewicz, *Myślenie sieciowe w teorii i praktyce*, PWE, Warszawa 2010; P.M. Senge, *Piąta dyscyplina. Teoria i praktyka organizacji uczących się*, Oficyna Ekonomiczna Wolters Kluwer Polska, Kraków 2006; K.R. Śliwa, *O Organizacjach Inteligentnych i rozwiązywaniu złożonych problemów zarządzania nimi*, Oficyna Wydawnicza WSM SIG, Warszawa 2001; Z. Souček, *Modelowanie i Projektowanie Systemów Gospodarczych*, PWE, Warszawa 1979; J. Tarajkowski (Ed.), *Elementy dynamiki systemów,* Wydawnictwo Akademii Ekonomicznej, Poznań 2008.

[4] B. Liwowski, *Działalność podstawowa przedsiębiorstwa i jej wyspecjalizowane zakresy* [in:] J. Kortan (Ed.), *Podstawy ekonomiki i zarządzania przedsiębiorstwem*, C.H. Beck, Warszawa 1997, p. 247.

[5] K. Kucińska, *Rynkowe uwarunkowania funkcjonowania przedsiębiorstwa* [in:] J. Kortan (Ed.), *Podstawy ekonomiki...,* p. 326.

Market analysis;
- Deciding on sales channels;
- Signing sales agreements with customers;
- Sales implementation;
- Organization of after-sales services;
- Conducting advertising;
- Managing the finished products warehous.

The current market orientation in which the consumer and market play dominant roles, resulting in all activities in the spheres of production and delivery being geerd towards meeting (and stimulating) customers‘ needs. The enterprise, therefore, needs to conduct marketing activitie if it is to fulfil market demands.

3. BUSINESS PROFILE OF ZELGRAF COMPANY

Zelgraf is a company in the small-scaled sector (www.zelgraf.com.pl) that has existed since 1996. It produces, amongst others, professional silicone matrices as well as steel matrices for pad printing, used for decorative labelling of glass and plastics. It specializes in matrices for labelling products in the automotive, cosmetics, fancy and house-hold appliances sectors. It has working agreements with companies such as Zelmer S.A., Rosti Sp. z o.o., OKT Polska oraz Joko Cosmetics.

The studies conducted in Zelgraf company focussed on the production of silicon stamps (otherwise known as silicon matices), which make it possible for products to be labelled whereever possible, even on curvatures. They are mainly suitable for labelling plastic products. They come in various sizes and shapes: flat, concave, convex, oval, square, round, spherical and triangular. Labelling takes place in the process of hot pressing of foils on any given location of the product.

Zelgraf produces stamps only for specific orders. Production is unitary, including eventual doublets, which are stored entirely in the producer's warehouse to be released to the customer only after the destruction of the first copy. The following sequence of steps is performed during production:
- Designing stamps, including the labelling locations on the product, namely graphics, shape and colour;
- The production process:producing the shaped matrices, control, preparing for production, preparing the stamp for production, the final product;
- Stamp checking and performance testing;
- Testing the labelled site for abrasion, adhesion and reaction with material from which the labelled material is made.

4. PRODUCTION-DELIVERY SIMULATION MODEL FOR ZELGRAF

The basis for the design was the model introduced by Sterman[6]. The model was modified by the authors of the foregoing paper and adapted to the profile of the company under study.

[6] J. Sterman, *Business Dynamics: Systems Thinking and Modeling for a Complex World*, Irwin McGraw-Hill, Boston 2000.

4.1. Definitions of variables for the mental model of the production-delivery system

The first step of the study was the observation of activities that formed part of the production-delivery process of the company covered by the study. Next, working in partnership with management and persons selected by the management the variables (parameters) for developing the mental model of the processes were set. The list of the parameters, including their definitions are contained in table 1.

Table 1. Mental model variables of the production and distribution

Variable	Description
Production start rate	Pace of directing individual factors to production
Production capacity	Real volume of production per specified unit of time, relative to the availability of objects of work (raw materials) and labour force
Possible production due to the availability of raw materials	Possible volume of production of finished products due to the availability of raw materials taken from the company's raw materials warehouse
Possible production due to the availability of labour force	Possible volume of production due to the availability of employed man power, that is characterized by a specific level of efficiency
Work in process inventory	Cumulative variable of the number of products currently in various stages of production
Completed production rate	The stream of finished production sent to the finished goods warehouse
Manufacturing cycle time	Time duration from the start to end of the production process
Desired production start rate	The desired volume of production per unit time, being the sum of the „Desired production", „Adjustment for work in process inventory" and „Correction of the desired production start rate of unaccomplished production"
Adjustment for work in process inventory	Responsible for adjusting the volume of production in process to the desired level
Desired work in process inventory	The desired volume of production in process proportionate to the „Desired production"
Work in process inventory adjustment time	Desired time duration for adjusting production volume in process to the desired level
Correction of the desired production start rate of unaccomplished production	Responsible for extending the „Desired production start rate" by the volume of outstanding production
Correction time	Time needed to correct the „Desired production start rate" with the volume of the outstanding production

Table 1 (contd). Mental model variables of the production and distribution

Variable	Description
Desired production	Desired volume of production per specified unit of time, being directly linked with the „Production orders”
Production orders	Number of orders sent for production
Customer orders	Number of orders received directly from customers
Finished products	Number of finished products, remaining in the finished products warehouse
Delivery rate	The pace of shipping finished products to the customers
Possible delivery rate	Possible number of finished products for a specified unit of time, that can be delivered to the client in direct proportion to the number of „Finished products” and inversley proportionate to the number of „Preparation time for delivery”
Preparation time for delivery	Time duration for activities connected with the preparation of finished products for shipment to the customer
Desired delivery rate	Desired number of finished products, that ought to be delivered to the customer at a specified time unit, resulting directly from the „Unrealized orders ” and „Planned delivery delay”
Unrealized orders	Number of orders received that were not accomplished and delivered to the customers
Orders rate	The stream of orders directed into production
Orders fulfillment rate	The stream of completed orders resulting directly from the „Delivery rate”
Unaccomplished production	Refers to the volume of unaccomplished production after the „Planned delivery delay”
Delivery delay	Time duration that specifies the current delay in accomplishment of incoming orders, assuming that the pace of orders accomplishment is the same as the variable value „Orders fulfillment rate”
Planned delivery delay	Planned incompany time duration that lapses from time of order placement till the delivery of ordered products

Source: own elaboration.

The selected variables were linked in cause and effect loops. This gave yield to a diagram of dependencies (Fig. 1), that is interpreted thus:incoming orders are for the company first signals to adequately adjust the level of production while still being in the stage of unaccomplished orders, that would later be accomplished after the production of ordered products. In the first case, „Customer orders" translates into „Production orders", which directly determines the „Desired production". The „Desired production" defines the new level of „Desired work in process inventory", which is comparable to the current level of „Work in process inventory". If disparities do exist between „Desired work in process inventory" and „Work in process inventory" then, adjustments are made „Adjustment for work in process inventory". The „Desired production" together with the „Adjustment for work in process inventory" determine the „Desired production start rate", which defines the size of „Production start rate".

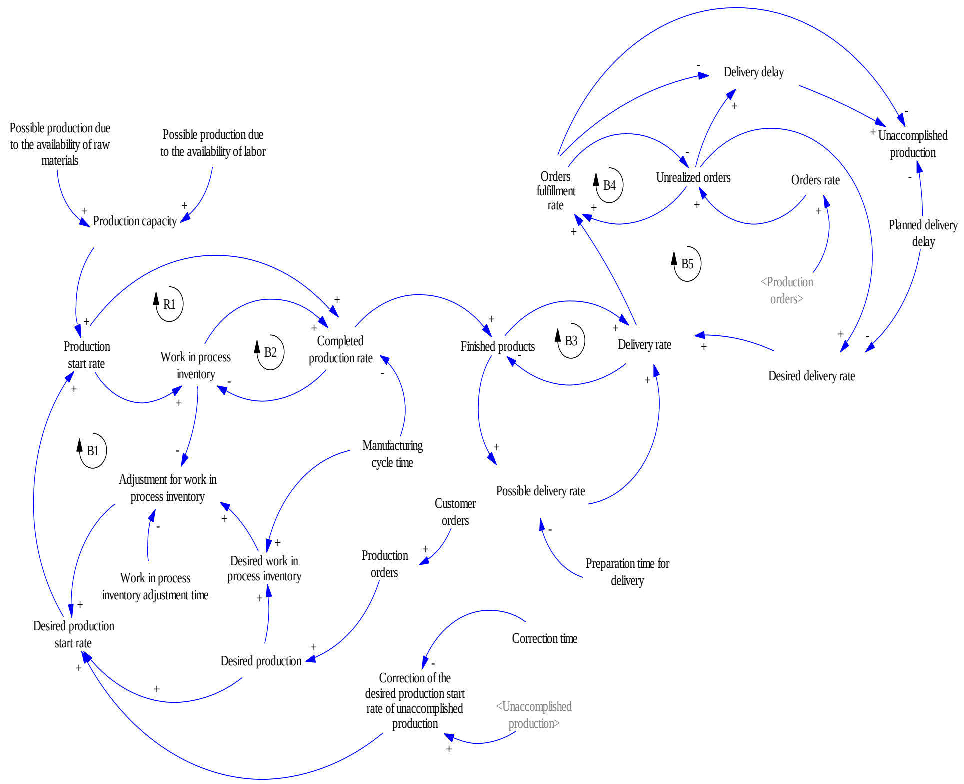
Having put together the relevant raw materials for production, and appointed a competent workforce production can begin. The volume of production which is determined by the size of orders awaiting accomplishment depends on the company's current production capacity, which in itself depends on the availability of appropriate volume of raw materials consumed in course of production as well as on the availability of workforce. The work items pass through successive phases of the production process, known as „Work in process inventory". The completion of the „Manufacturing cycle time" is followed by the „Completed production rate", that result in the finished products getting to the warehouse „Finished products ". They are then packaged and prepared in the warehouse for delivery to the customers.

The factual „Delivery rate" depends on both the „Possible delivery rate" and the „Desired delivery rate". The „Possible delivery rate" is determined by the availability of stock of finished products, namely produced items ordered by customers. The „Desired delivery rate", on the other hand, determines th number of „Unrealized orders" as well as the „Planned delivery delay". The „Planned delivery delay" in such cases is the time planned by the company that runs from the moment of order placement by the customer till the accomplishment of the order.

Besides the „Planned delivery delay" there also exists a „Delivery delay", being the result of the accumulation of „Unrealized orders". Whenever „Delivery delay" time surpasses the „Planned delivery delay" time, the accumulation of „Unaccomplished production " occurs. Information concerning „Unaccomplished production" via the „Correction of the desired production start rate of unaccomplished production" additionally increases the „Desired production start rate".

The diagram contains five simple negative feedbacks: B1, B2, B3, B4 i B5 and one positive feedback – R1, thus confirming the continuity of regulatory processes and dynamics that exist within the system.

Fig. 1. A diagram of dependencies within the production-delivery model



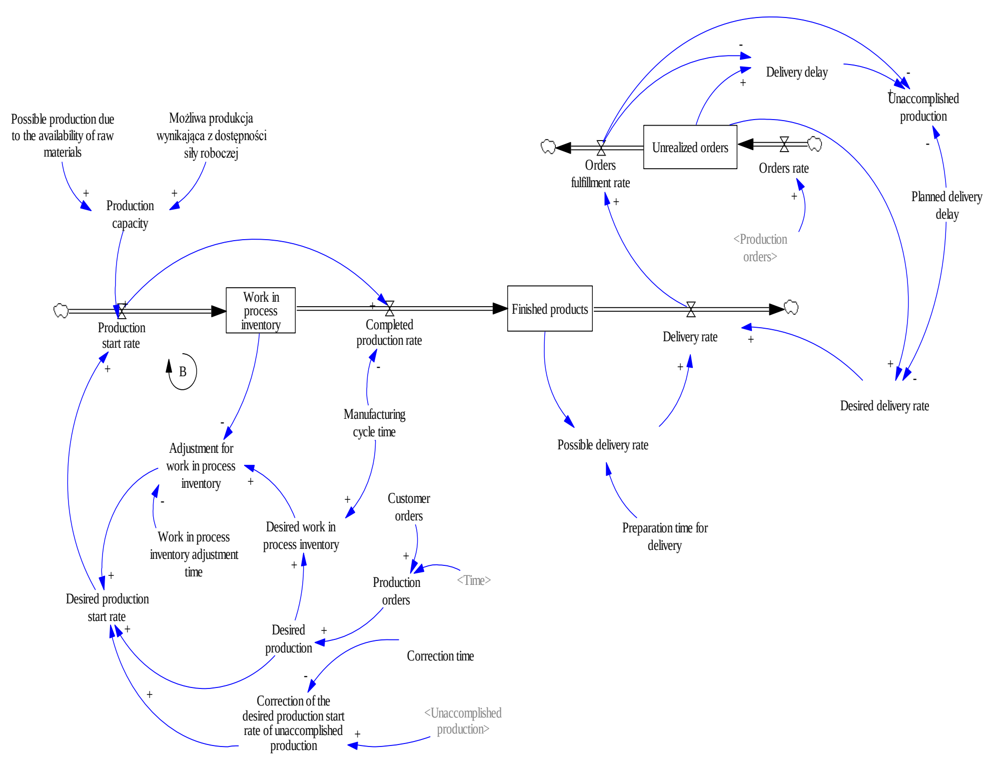
Source: own elaboration.

4.2. Simulation Model

The next stage involved the development of a simulatory production-delivery model using Vensim® DSS software (www.vensim.com) (Fig. 2). The variables adopted earlier were transformed into accumulatory, flow and information as well as stable information variables for which respective numeric data (using empirical studies) were assigned.

The simulation model was developed based on the convention of methods of dynamic systems. The method relies on three pillars, namely on traditional management, principles of cybernetics and computer simulation. Traditional management helps in identifying problems or issues related to the system that will be modeled. It assists in the proper selection of variables that impact on the behaviour of the system and indicates the flow-path of information between the variables. It formulates decision principles responsible for controlling the model. Cybernetics is responsible for linking the selected variables in the model, building positive or negative feedback loops and also helps in structuring the mathematical model of the model being developed. Resolving such a model, that often involves non-linear dependencies requires appropriate numerical methods, which in the case of dynamic systems is a computerized simulation[7].

Fig. 2. A simulation model of the PRODUCTION-DELIVERY system



Source: own elaboration (VENSIM DSS).

The consists of three accumulative variables:

- „Work in process inventory" increased by the flow variable „Production start rate" and decreased by the next flow variable „Completed production rate";
- „Finished products" increased by „Completed production rate" and decreased by „Delivery rate";
- „Unrealized orders" increased by„Orders rate" and decreased by „Orders fulfillment rate".

[7] M. Baran, J. Stecko, *Symulacyjny model gospodarki – przypadek przedsiębiorstwa Fotosystem*, „Humanities and Social Sciences" 2013/20, pp. 29–40.

The rest of the variables and constants only play subsidiary and informative roles. The mathematical relation between the variables and constants of this part together with their units are summarized in table 2.

Table 2. Definitions of variables and constants used in the simulation model

Variable	Description	Unit
Production start rate	MIN (Production capacity, Desired production start rate)	[unit/week]
Production capacity	MIN (Possible production due to the availability of labour force, Possible production due to the availability of raw materials)	[unit/week]
Possible production due to the availability of labour force	70 (averaged empirical data)	[unit/week]
Possible production due to the availability of raw materials	100 (averaged empirical data)	[unit/week]
Work in process inventory	INTEG (Production start rate-Completed production rate) Initial Value: Desired work in process inventory	[unit]
Completed production rate	DELAY3 (Production start rate, Manufacturing cycle time)	[unit/week]
Manufacturing cycle time	1 (averaged empirical data)	[week]
Desired production start rate	MAX (0, Desired production+Adjustment for work in process inventory+Correction of the desired production start rate of unaccomplished production)	[unit/week]
Adjustment for work in process inventory	(Desired work in process inventory-Work in process inventory)/Work in process inventory adjustment time	[unit/week]
Desired work in process inventory	Manufacturing cycle time*Desired production	[unit]
Work in process inventory adjustment time	0,2 (averaged empirical data)	[week]
Correction of the desired production start rate of unaccomplished production	Unaccomplished production/Correction time	[unit/week]

Table 2 (contd). Definitions of variables and constants used in the simulation model

Variable	Description	Unit
Correction time	0,05 (averaged empirical data)	[week]
Desired production	MAX (0, Production orders)	[unit/week]
Production orders	MAX (0, Customer orders (Time))	[unit/week]
Customer orders	[(0,0)-(60,600)], (0,12), (1,17), (2,10), (3,12), (4,24), (5,8), (6,5), (7,20), (8,16), (9,31), (10,7), (11,5), (12,8), (13,19), (14,6), (15,27), (16,12), (17,5), (18,5), (19,13), (20,5), (21,21), (22,23), (23,5), (24,0), (25,0), (26,0), (27,4), (28,11), (29,3), (30,9), (31,12), (32,7), (33,17), (34,24), (35,21), (36,4), (37,5), (38,10), (39,35), (40,14), (41,8), (42,14), (43,42), (44,0), (45,23), (46,13), (47,5), (48,9), (49,6), (50,2), (51,38), (52,15), (53,10), (54,0), (55,14), (56,10), (57,16), (58,26), (59,51), (60,13)	[unit/week]
Finished products	INTEG (Completed production rate-Delivery rate) Initial Value: 0	[unit]
Delivery rate	MIN (Possible delivery rate, Desired delivery rate)	[unit/week]
Possible delivery rate	Finished products/Preparation time for delivery	[unit/week]
Preparation time for delivery	0,2 (averaged empirical data)	[week]
Desired delivery rate	Unrealized orders/Planned delivery delay	[unit/week]
Unrealized orders	INTEG (Orders rate-Orders fulfillment rate) Initial Value: 0	[unit]
Orders rate	Production orders	[unit/week]
Orders fulfillment rate	Delivery rate	[unit/week]
Unaccomplished production	IF THEN ELSE (Delivery delay/Planned delivery delay>1, (Delivery delay*Orders fulfillment rate-Planned delivery delay*Orders fulfillment rate), 0)	[unit/week]
Delivery delay	Unrealized orders/MAX (1,Orders fulfillment rate)	[week]
Planned delivery delay	1 (averaged empirical data)	[week]

Source: own elaboration.

The time unit adopted for the model was a 5-day working week. The constant values were hence converted into the adopted unit, making 1 day to equal 0.2 week. The mean average for the data collected for each constant was calculated. In describing the variables the functions (MIN, MAX, DELAY3, IF THEN ELSE) available in the library of the VENSIM DSS software were applied.

4.3. Validation of the simulation model

The validation of the propriety of the model was undertaken in subsequent studies using the following methods:

- Assessment of the propriety of choice of modelling limits (boundaries), propriety of the model, structure and the consistency of the adopted parameters (for fixed models) in comparison with available knowledge concerning the modelled system;
- Testing the propriety and consistency of the variable units adopted for the model;
- Testing the functioning of the model under imposed stress conditions.

The main purpose of developing the model was to map, in general, the production and delivery system in a manufacturing company along with its key decisive principles for controling the system. Hence such variables that were quantitatively contained in the tested system were chosen. The management of the respective company and other experts participated in both the choice of variables for the model and in the creation of its structure. Scientific literature was also made use of. The parameter values adopted for the needs of the model were provided by persons authorized by management. The mean average for all the parameter values (fixed models) were calculated by the same persons. All this is to prove the proprietness of the choice of modelling limits and the structure of the tested system, including the propriety of the value parameters for the model adopted.

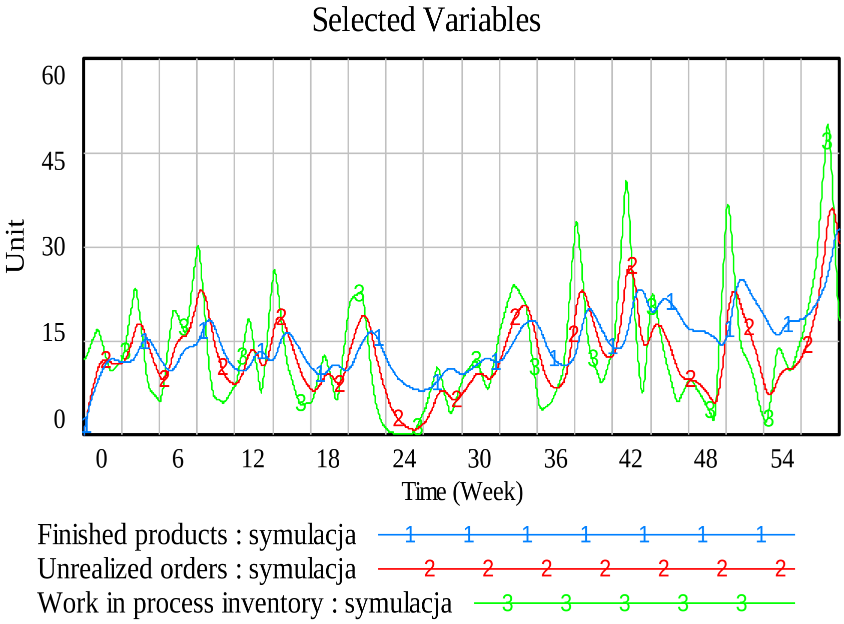
One of the basic measures for difining the correctness of links between variables in the model and also responsible for the overall proprietness of the model is the test of consistency of the variable units adopted for the model. The test was conducted directly in the program, in which the model was developed, using the commands *Units Check* in the tab *Model*. The correctness of the unit was confirmed.

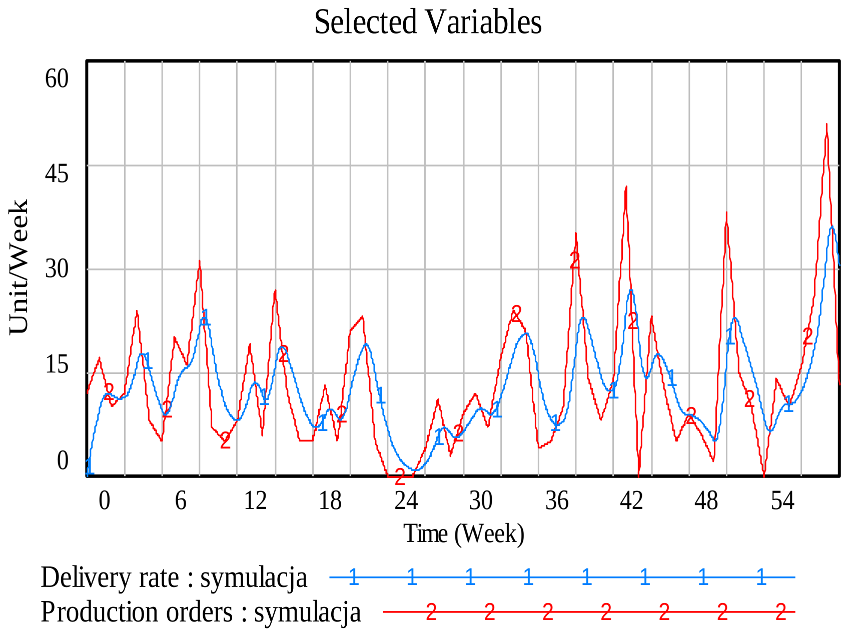
Testing the model by using stressful conditions was meant to check its performance when the fixed values amounted to 0 or very large values. The program, in the course of this testing, signaled several times the surpassing of the numerical range by values of some variables leading to the interruption of the simulation. These were mainly the variables, which while appearing in the descriptive equations of the model, in the denominator of the expression took on the value of 0. To eliminate such errors the MAX function was applied in defining such variables.

5. MODEL SIMULATION

Having completed the simulation model with the data contained in table 2, the simulation was conducted. The step of simulation was assumed to be 0.03125. The course of the accumulatory variables as well as the variable „Production orders" and „Delivery rate" in the tested time period of 60 weeks is illustrated in the graphs below (Fig. 3)

Fig. 3. The course of selected variables of the PRODUCTION-DELIVERY system



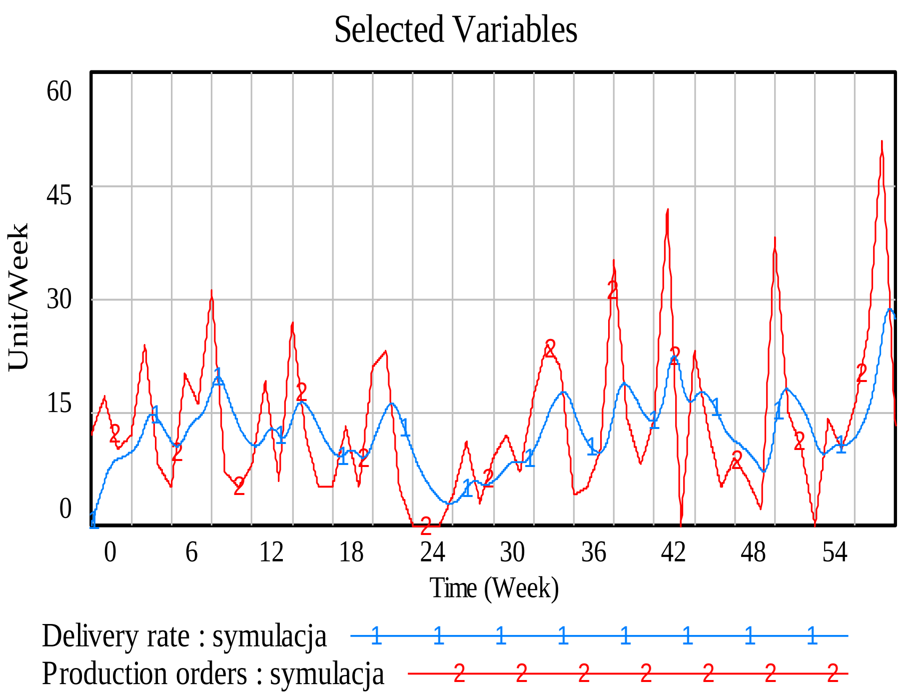


Source: own elaboration (VENSIM DSS).

The volume of the orders had direct impact on the behavioral dynamics of the accumulatory variables of the PRODUCTION-DELIVERY system. The first graph on chart 3 shows their changeability and fluctuation in each week. It should be noted that values of these variables are integral building blocks between the flow variables. The second graph depicts the course of two variables, namely „Production orders" as well as „Delivery rate". The values of the first variable were the results of empirical studies conducted. The values, on the other hand, are simulated values. Time lags between the values of the two variables, due to the size of the „Planned delivery delay" (1 week) can be observed.

The simulation of the model allows for the testing of varied scenarios related to the system being tested, type „if...then...". For example, one can check how the value of the variable „Delivery rate" chandes if „Planned delivery delay" is prolonged to 2 weeks. The path of the variable in illustrated in Fig. 4.

Fig. 4. Values of „Delivery rate" for „Planned delivery delay" for 2 weeks



Source: own elaboration (VENSIM DSS).

6. CONCLUSIONS

The paper contained a description of the methodology for constructing a simulation model of the PRODUCTION-DELIVERY system, using Zelgraf company as a case study. The modelling of the system made it possible to identify each on-going processes in the system and has also made their graphic presentation of the order possible. This has had a positive impact on the overall analysis of the entire system. Additionally, the simulation model developed has enabled the conduct of several testings related to the verification of set strategies for managing the system in the company under study. The current model is suitable for use in Zelgraf company in the following processes:

- Observation of dynamic relationships between the building blocks variables of the PRODUCTION-DELIVERY system;
- Forecasting the behaviour of the PRODUCTION-DELIVERY system in response to the changing environment (expressed by changing the values of fixed parameters of the model or by adding new fixed parameters);
- Planning and deciding in respect to the management of the system;
- Training for employees and young executives.

The illustrated model is suitable for use also in other companies of similar line of business, that can adapt it to their personal needs and environment.

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SYMULACYJNY MODEL PRODUKCJA-ZBYT W KONWENCJI METODY DYNAMIKI SYSTEMÓW. PRZYPADEK PRZEDSIĘBIORSTWA ZELGRAF

W artykule przedstawiono kolejne kroki budowy modelu symulacyjnego systemu produkcji i zbytu w przedsiębiorstwie produkcyjnym. Początkowo wytłumaczono istotę procesów produkcji i zbytu, czyli kluczowych procesów wchodzących w skład działalności podstawowej przedsiębiorstwa produkcyjnego. Wskazano i krótko scharakteryzowano najważniejsze reguły decyzyjne powiązane bezpośrednio z tymi procesami. Następnie przedstawiono profil działalności przedsiębiorstwa produkcyjnego Zelgraf, w którym przeprowadzono badania mające na celu praktyczne zapoznanie się z wymienionymi procesami. Dzięki tej znajomości wyłoniono zmienne modelu myślowego związanego z procesami produkcji i zbytu, które zestawiono tabelarycznie. Zmienne modelu myślowego powiązano w diagram przyczynowo-skutkowy, będący podstawą do opracowania modelu symulacyjnego. W diagramie zaznaczono charakterystyczne rodzaje sprzężeń zwrotnych działających w badanym systemie świadczących o ciągłych procesach regulacji. Na podstawie diagramu przyczynowo – skutkowego opracowano docelowy model symulacyjny. Wykorzystano tu metodę dynamiki systemów. Zarówno do budowy modelu, jak i symulacji wykorzystano oprogramowanie Vensim® DSS. Posługując się językiem oprogramowania podano poszczególne definicje zmiennych oraz wartości stałych dla modelu. Wartości te wynikały bezpośrednio z przeprowadzonych badań empirycznych w wybranym przedsiębiorstwie. W kolejnym kroku dokonano walidacji modelu symulacyjnego w oparciu o trzy metody: oceny poprawności wyboru granic modelowania, poprawności struktury modelu oraz spójności przyjętych wartości parametrów (stałych modelu) w porównaniu z dostępną wiedzą na temat modelowanego systemu; testu poprawności i spójności jednostek zmiennych przyjętych w modelu oraz testu działania modelu przy narzuconych warunkach skrajnych. Metody potwierdziły poprawność modelu. W ostatnim etapie przeprowadzono symulację modelu dla przyjętego kroku, przedstawiono przebiegi zmiennych akumulacyjnych oraz wybranych zmiennych systemu i dokonano analizy otrzymanych wyników. Przedstawiono także jeden scenariusz testów związanych z badanym systemem. W podsumowaniu wskazano praktyczne możliwości wykorzystania opracowanego modelu.

Słowa kluczowe: produkcja, zbyt, modelowanie symulacyjne, dynamika systemów

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