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Study of Changes in the Production Process Based in Graph Theory

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1. Introduction

New areas of knowledge can only be created based on earlier scientific output. To identify possible cognitive gaps, the existing knowledge of management was analysed, which allowed dividing the knowledge hierarchically into three levels of organizational management, enterprise management and production management. The lowest position of the last level in the hierarchy does not make it is less important, especially in the present economic situation of the world that struggles with the impacts of the global crisis.

Graph theory is a field of knowledge offering a broad range of applications. A novel approach was using the theory to build a production management model based on the concept of an inverted tree (with many entries and one exit), as this type of a model reflects the real-life determinants affecting the production of short life cycle goods. The conducted investigation involved clothing companies that produce such goods. Clothing manufacturers deciding to start production invariably expose themselves to considerable risk. This risk can be reduced by obtaining more information on customers' expectations, fashion trends, the conditions of acquiring materials necessary for making the designed models, as well as manufacturer's technical and technological capacity for actually producing the garment. One assumption as made during the investigation was that the analysed product would not be a single design, but a series of garments comprising a fashion collection [6]. It was also necessary to assume a process-based approach to production management that in the opinion of many authors boosts enterprise effectiveness [5, 7]. With these assumptions in mind, the production process was broken down into four main subprocesses (product creation, setting up product manufacturing, manufacturing and sale) and their subdivisions. The presented production management model is based on this breakdown.

According to the research, apparel as a category of the short life-cycle goods is made in a production process (consisting of product creation, the setting up of the manufacturing processes, procurement of intermediate materials and sale) that spans 18 months [6]. In this relatively long time, the actual production circumstances and those predicted at the planning stage are very likely to show significant differences. Why the changes appear will not be explored in the article to keep it concise, but their occurrence will be assumed *a priori* as a fact. This study was designed to investigate the negative effects of the changes delaying the completion of a production process.

It must be remembered that the production cycle for the short life-cycle goods has a pre-determined date when the sale should start. The fact that the delays observed during the research usually resulted from management errors committed for a lack of an appropriate tool aiding production management helped identify a cognitive gap, following which a method for analysing process changes was developed. The method was called a Production Process Control Tree (PPCT).

2. The production cycle model for short life cycle models

2.1 Short life cycle products

The investigation concentrated on production management that in the theory of management deals with providing scientific solutions to production problems. Concentrating on processes „and not on jobs, people, structures and functions makes it possible to watch the main purpose of the process and not its components" [11]. The process-based approach was adopted to create a production cycle model for short life cycle products (SLCP). The term "life cycle" has been „derived from natural sciences, after an analogy between living organisms and products was found. They are too destined to be born, mature, age and die" [1]. The popularity of the term increased with the European Commission's project of 2005 *„The European Platform on Life Cycle Assessment (LCA)"* [25], which extended the notion of life cycle over business and politics. These circumstances increasingly justify the search for regular patterns (cycles, loops, or equilibrium points) that systems tend to [16]. The role of product life cycle was also commented on by P.F. Drucker [3], who stated that it could be used as a tool for evaluating firm's position. Further, R. Kleine-Doepke [12] mentioned life cycle together with the experience curve concept and the results of research conducted under the PIMS (*Profit Impact of Market Strategy*) program, as the third of the factors that contributed to the development of the portfolio planning methods. All these circumstances provided an inspiration for focusing the study on the management of production of the short life cycle products. Such products have one of the below characteristics:

- the length of the selling period depends on product design, and fashion shows cyclical changes,
- the end of the production period is determined by objective constraints on sales (e.g. alternating seasons in the case of clothing),
- the length of production cycle is incommensurate with the selling period.

Typical products whose life cycle is decided by their design are clothing and footwear. Their selling time is correlated with the passing of seasons that together with the seasonal character of fashion trends subject production management to strict discipline. Products manufactured for too long become unsaleable. The manufacturers of durable goods use the positive aspect of fashion to stimulate demand (motor vehicles, interior design articles, etc.).

2.2 Formulation of the research hypothesis

According to M. Marchesnay [19], a theory is constructed via a process consisting of the following stages: formulation of a hypothesis, construction of a hypothesis confirmation procedure, confirmation by means of an empirical test or mathematical-logical evidence, assessment of the confirmation success rate, formulation of conclusions (theoretical/practical). This sequence is criticised by persons advocating the phenomenological approach who believe that understanding the examined phenomena is more important than measuring them. This approach is justified in the case of a heuristic research and scientific procedure. However, M. Marchesnay's procedures are appropriate when the researcher's reasoning is linear. With these reservations in mind, the following hypothesis was formulated:

The management of production of the short life cycle products is a process of determined duration, consisting of four cyclical subprocesses. The cycles are staggered with respect to each other by fixed time intervals.

For the hypothesis to be confirmed an appropriate investigation had to be conducted and its results analysed. The management science proposes in this case a three-stage model of analysis comprising decomposition (into the building blocks), description and integration [23]. The presented algorithm was used at the further stages of the investigation.

2.3 Process decomposition and a description of its components

The process applied to produce garments was divided into four main sub-processes: product development, preparation of production, production and sales. As far as the short life cycle products are concerned, separating product development from all other actions related to the production preparation process is justified. An example of the SLCP is fashion articles whose production is determined by seasonality of sales. Two fashion collections are usually created, i.e. for the spring-summer and autumn-winter seasons.

2.3.1 The garment development subprocess

This subprocess is carried out between 1 February (of the year preceding product release) and 1 August for the spring-summer collection and between 1 August and 1 February of the next year for the autumn-winter collection.

New product designs are created based on the external and internal sources of information. The latter usually account for more than 55% [15]. This rate, however, does not apply to fashion articles. Their originality is assessed by means of criteria laid out in the copyrights. For a season's collection to be created, information has to be collected from several sources:

- design guidelines formulated by fashion creators,
- data provided by a survey of a market segment targeted by the enterprise,
- information about the relevant garment constructions and manufacturing technologies that will be used subject to the availability of appropriate equipment.

A talented designer and the person's ability to assimilate the design guidelines, whose new informative contents alter the knowledge of the trends in fashion development, are a prerequisite for starting the work on a collection. The relevant guidelines can be sought in Paris, Milan, etc., at international fashion shows. As observed, some fashion elements are recurrent; yet, they are never copied, but introduced after some modifications. This justifies the statement that all models of a season's collection are new. Products that are attractive for the buyers (because of their design, quality and price) involve interaction with the customers. Data offered by market surveys are an important source of information, allowing the manufacturer to look at a product from a broader perspective [18]. However, a design that is attractive but priced against the expectations of the targeted market segment will render sales unsuccessful. The responsibility for setting prices rests on an authorised group of persons who take account of the design manufacturing data (material and labour costs, etc.). Design attractiveness is the main criterion affecting the level of prices. A market failure is certain when the season's collection is released too late. This fact demonstrates the importance of the time factor for the production cycle of seasonal products.

2.3.2 The production preparation subprocess

This subprocess is carried out between 1 June and 1 December for the spring-summer collection and between 1 December and 1 June of the next year for the autumn-winter collection.

The production preparation subprocess consists of:

- preparation of the technical and technological documentation,
- procurement of the necessary materials,
- planning and organizing the product manufacturing subprocess.

From the standpoint of the operations to be carried out within the production preparation subprocess, it is not important whether the team of workers responsible for the subprocess will be based in their parent company or at the service provider's site [9]. The technology to be used must correspond to the selected materials and the available machines (either owned or belonging to other party). Modern enterprises prepare the necessary documentation using Computer Aided Manufacturing systems (CAD) that are common in the Polish medium and large-sized manufacturing companies today. The author pioneered the implementation of the first of such systems in Poland in 1987. Other activities related to the preparation of documentation include:

- sequencing the technological operations,
- selecting the machines and pieces of equipment necessary to perform the operations,
- calculating the times necessary to complete each operation.

These documents allow setting up the product manufacturing subprocess, estimating the wages to be paid to the piece-rate workers, the direct production costs, etc.

Material procurement, which is a separate activity, is equally important. The domestic clothing industry buys its materials from suppliers based in the EU (the high end of the apparel market) and in Asian countries (the other segments). The geography of the suppliers usually has a bearing on fabric quality, wearability and price, the latter being a key factor shaping the final price of a product. Fabric patterns are picked by the designers who take into account the designs to be produced, while the procurement personnel is responsible for analysing the submitted offers and making choices that are optimal for the firm. All procurement, although the contract signing process is exposed to the pressure of time, must be carried out prudently. The type of payment (advance payment, pay on delivery, deferred payment) is an important aspect of negotiations concerning the terms of supply. Optimization of the procurement process is vital for enterprise functioning.

The organizational setup of the product manufacturing process must integrate the following areas:

- human (the necessary number of workers with the required skills and available at the right time and place),
- technical (the availability of the machines and equipment),
- material (the optimal quantity of materials stored in the working areas and available when needed).

The above areas decide about the type of the manufacturing system that will be used: an assembly line, an assembly line with sections, sections with synchronised working teams, a flow system or an arrhythmic system [27]. Other factors that influence the production preparation process include the size of an order, the possibility of making several models simultaneously, etc. The organizational efforts must optimize manufacturing times and costs, as well as providing a product of expected quality (in relation to manufacturers' expenses and target buyers' preferences).

2.3.3 The product manufacturing subprocess

This subprocess is carried out between 1 August and 1 February of the next year for the spring-summer collection and between 1 February and 1 August for the autumn-winter collection.

A characteristic feature of garment production is the input of manual labour. In the developed countries, small series of garments containing particular large inputs of manual labour are produced for the high-end market segments. Regardless of the target buyer, garment production consists of two main stages: cutting out garment elements and their assembly. The operations performed at the two stages depend on the organizational plan and technological documentation prepared beforehand.

The first of the two stages comprises the following operations:

- fabric layers are spread along the cutting table to form a stack (in a manual or automated process),
- the layout of the templates to be cut out is transferred on the stack of fabric,
- garment elements are cut out from the fabric with dies, portable oscillating knives, stationary cutting machines, or automated cutting systems,
- adhesive inserts are bonded with the cut-out elements or sections thereof that need stiffening / strengthening,
- the cut-out elements are numbered/marked,
- the cut-out elements are checked for quality,
- the cut-out elements are bundled up (e.g. 50-piece bundles) and stored.

The cutting room setup aims at keeping the cutting machine busy at all times, as the machine is a central piece of equipment that decides about the output of the semi-finished products. The continuous operation of the cutting machine can be ensured via one of two modes. The first of them requires the keeping of spare stacks of laid-out fabric, which increases the amount of work in progress. The second method allows accomplishing a steady workflow by feeding into the machine sections of stacked fabric that are prepared simultaneously on two or several tables. Therefore, the cutting room operations are mainly determined by the available equipment.

The cut-out elements are then transported to the sewing room so that a finished product can be assembled. The garment assembly process is preceded by the following procedures:

- reorganization of the working team as required by the technical and technological documentation, allowing for the installation of the necessary machines and equipment and the verification of their reliability,
- cooperation with the Production Preparation Department in making a model ready for production.

All technological operations in the sewing room can be divided into three groups:

- sewing,
- adhesive bonding,
- thermal processing of a product.

Thread joints are the basic technology employed in garment manufacturing. The sewing machines are divided into universal, semi-automated and automated machines. The automated sewing machines are the state-of-the art technology, but garment complexity makes them more appropriate for performing specific jobs or making simple products. Stitching quality is assessed against the in-house standards, as it ultimately affects the quality of a finished product.

Adhesive bonding makes use of a diffusion process that takes place between adhesive particles and the substrate. Adhesive joints are divided into bonded, heated and welded. A popular adhesive bonding method is contact heating. In most cases, two layers of fabric are bonded together with an adhesive. The elements to be bonded are heated on one side and then mechanically pressed together. The bonding process can be applied to a surface (e.g. inserts reinforcing the chest elements of a jacket), linearly (adhesive stitching) or in a dot-like manner. The criterion for the division is the area exposed to bonding. Adhesive bonding is now an important part of the garment manufacturing process, greatly reducing its time.

In terms of technology, the thermal processing of garments can be divided into:

- forming, i.e. the shaping of garment elements by applying force, temperature and by moistening, is a major process in the production of heavy garments (overcoats), as the shape of their elements depends also on factors other than the construction of particular elements alone;
- product upgrading by pleating, applying permanent press, as well as surface or local dyeing of finished products in which process the design is transferred from a paper template onto the product by pressing them together;
- steaming that involves the use of steaming dummies in order to remove minor workmanship defects or to freshen up a product after it has been stored for a long time or cleaned;
- the interim pressing operations performed at different stages of the assembly process; they have a strong effect on the quality of final pressing and are carried out immediately after the cut-out elements have been joined together, as after attaching the lining such joints become inaccessible;
- final pressing that determines the ultimate product quality; the operation can be performed with a whole range of specialist machines and pieces of equipment.

Smart clothes are different from the other types of clothing not because of their construction (that can be copied) but due to fabric quality, the quality of the assembly process and thermal processing.

2.3.4 The sales subprocess

This subprocess is carried out between 1 February and 1 August (one year after the product development process was started) for the spring-summer collection and between 1 August and 1 February for the autumn-winter collection.

The Kotler model [14] as applied to the sales subprocess is well known, so it will not be discussed here to make the article concise. Because the scientific output in this field is considerable, it was decided that repeating it would be pointless.

3. Product life cycle and production cycle

The earlier quoted authors suggested that it was possible to present research results as a Kotler curve [14] extended to include the earlier subprocesses. The curve describes a product life cycle as sales in time (fig. 1).

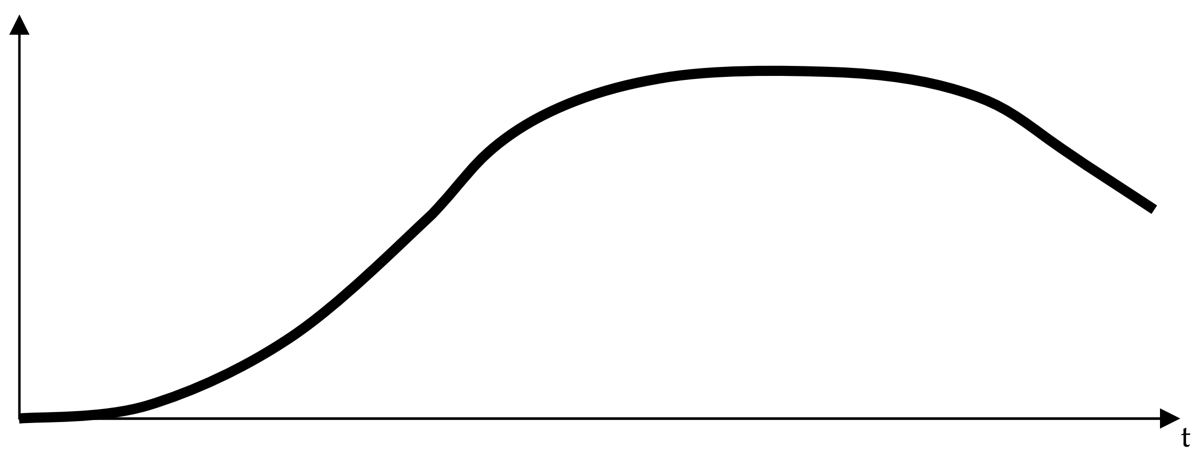

Fig. 1. Product life cycle – Kotler curve
Source: developed after Ph. Kotler, *Marketing Management, 11th ed.*, Prentice Hall 2003, p. 328

According to Kotler [14], the sales curves vary depending on the product (fig. 2):

A. stylish products (architecture, furniture, etc.),
B. fashion articles (clothing, footwear etc.),
C. products with temporary popularity (Rubik's cube, yo-yo, etc.).

The B curve reveals some special character of the fashion articles. The graph is fully adequate when a fashion article is meant as one model of a product. However, the investigation has confirmed that the classical product life cycle approach can be applied to clothing too (fig. 1), if we assume that such products do not represent a single design but a set of designs comprising a seasonal offer, which is in fact the final product of an enterprise. This knowledge encouraged the author to present the investigation's findings graphically as a Kotler curve extended to include the earlier production management subprocesses. Consequently, an original production cycle model for the SLCP was created, approximating the temporal work intensity distribution in the particular components of the production process. According to Waszczyk and Szczerbicki [26], such approximation is rarely treated as model falsification. It is rather assumed that some developments taking place in the economic reality were omitted from the model. The Leśkiewicz [17] accuse the approach of being internally inconsistent, i.e. combining unrealistic assumptions and a strongly accentuated previdistic function of the economy. Nevertheless, Waszczyk and Szczerbicki [26] view things differently: a solid description provided at the stage of constructing an explanatory model lends credence to its prognostic value. The long-time research conducted by the author of this article allows her to confirm this opinion.

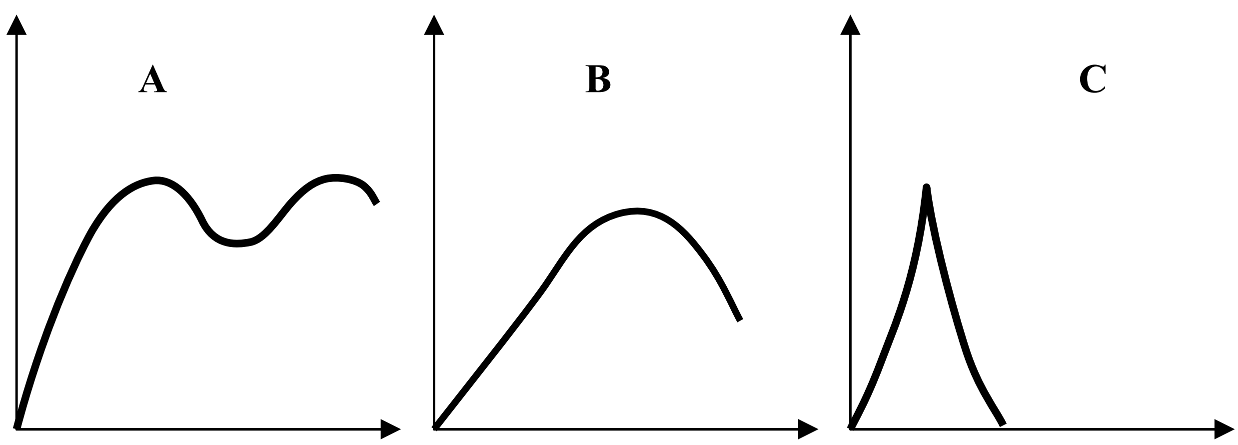

Fig. 2. Life cycles: A – stylish products, B – fashion articles, C – temporarily popular products.
Source: developed after Ph. Kotler, *Marketing…*, op. cit., p. 330

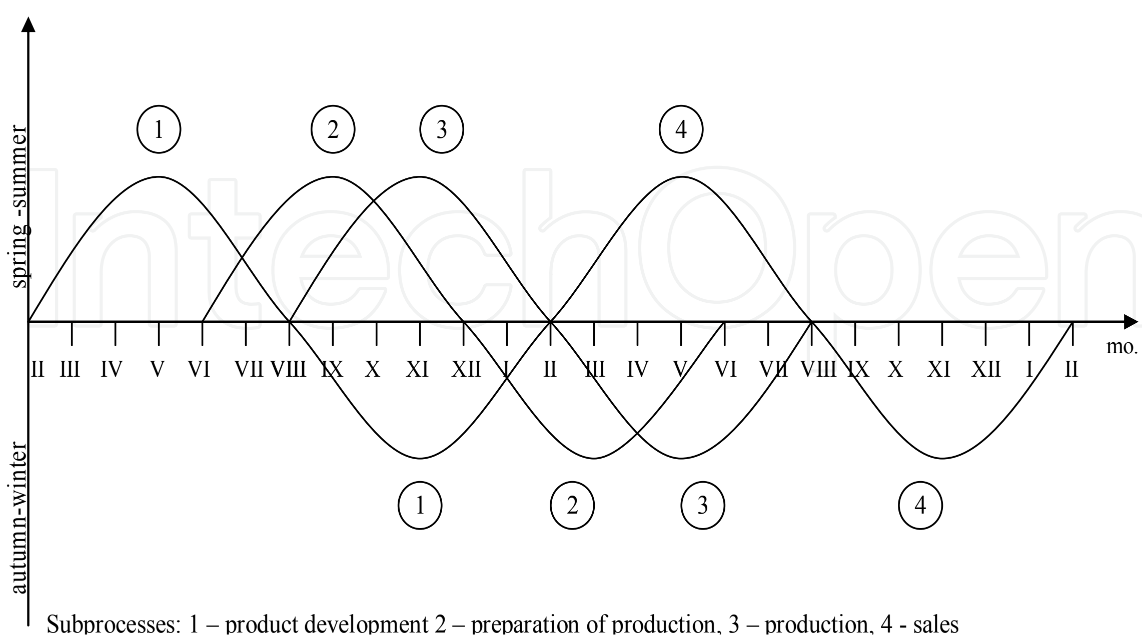

Fig. 3. The SLCP production cycle model.
Source: developed by the author.

The constructed production cycle model (fig. 3) is underpinned by the author's empirical study, the findings of which were verified in the course of her 18 years' long business practice. Although the changing circumstances impeded the correct time measurements, the cyclical character of the production process enabled their verification. For the model to be created „the reality had to be appropriately smoothed out" [12]. It is justified to state now that the presented model sufficiently reflects the actual situation. Author's good knowledge of the research subject is confirmed by the attached description of the production process. All these circumstances together allow concluding that the evaluation [26] of the constructed model' prognostic properties is fully relevant.

In the presented production cycle model, sales are only one of the subprocesses (curve 4). The *x*-axis separates operations necessary to prepare two clothing collections in a year; these related to the spring-summer season run above the axis, while operations concerning the autumn-winter collection are below it. The curves illustrate the rising and falling intensity of work in the particular subprocesses during the execution of a seasonal collection, as well as determining their acceptable completion times. The curves are shifted with respect to each other by a time interval indicated by the research findings. Although it is possible for the interval to show minor variations, the regular occurrence of a constant time interval is a fact. The interval is:

- four months between curves 1 and 2,
- only two months between curves 2 and 3,
- as many as six months between curves 3 and 4.

Because each of the four subprocesses goes on for as long as 6 months, the production process could be spread over 24 months. The possibility of reducing the time by four months (between curves 1 and 2) and two months (between curves 2 and 3) as demonstrated by the research findings shortens the production process to 18 months. It is also worth noting that the start dates for the spring-summer collection (curve 1 above axis *x*) and the autumn-winter collection (curve 1 below axis *x*) are shifted against each other by 6 months. The knowledge of this fact allows optimizing the management of production of seasonal products having a determined manufacturing completion time.

4. A production management model for short life-cycle goods

Production management must always arise from a plan. Every „plan involves a performance imperative. An organization striving to comply with the imperative becomes less flexible and less perceptive of what is going on around it. On the other hand, the increasingly turbulent environment requires organizations to show flexibility, so that unexpected events […] representing opportunities can be used, while those posing threats avoided […] "[16]. The changes in the functioning of domestic enterprises are well illustrated by the events that took place at the turn of the 20th c., which demonstrated how the transition of 1989 contributed to the formation of a new economic reality in Poland [7]. After the domestic market was opened, the inflow of imports increased. As a result, stronger competition in the market reduced the range of selling opportunities. These circumstances substantiate an investigation into the ways of improving the effectiveness of production management that provides companies with more favourable market positions.

A production management model for the short life-cycle goods was built following the stages below:

Stage I. Empirical aggregation of actions making up the production process.
Stage II. Using the Altshuller method for verifying causal relationships between particular actions.
Stage III. Making a schedule of the actions and determining their times.
Stage IV. Building the model based on graph theory.

The fact that the author had researched the area for many years helped verify the process constituents and the causal relationships between them were found using the Altshuller method. For the sake of illustration, let us show the applied method with respect to the subprocess representing the creation of a fashion collection.

The evaluation of the attractiveness of clothing designs (5) is the critical action in the string of events presented in diagram 1. The acceptance of the designs means that the next steps can be taken, i.e. the sample room team can prepare a sample of the designed model.

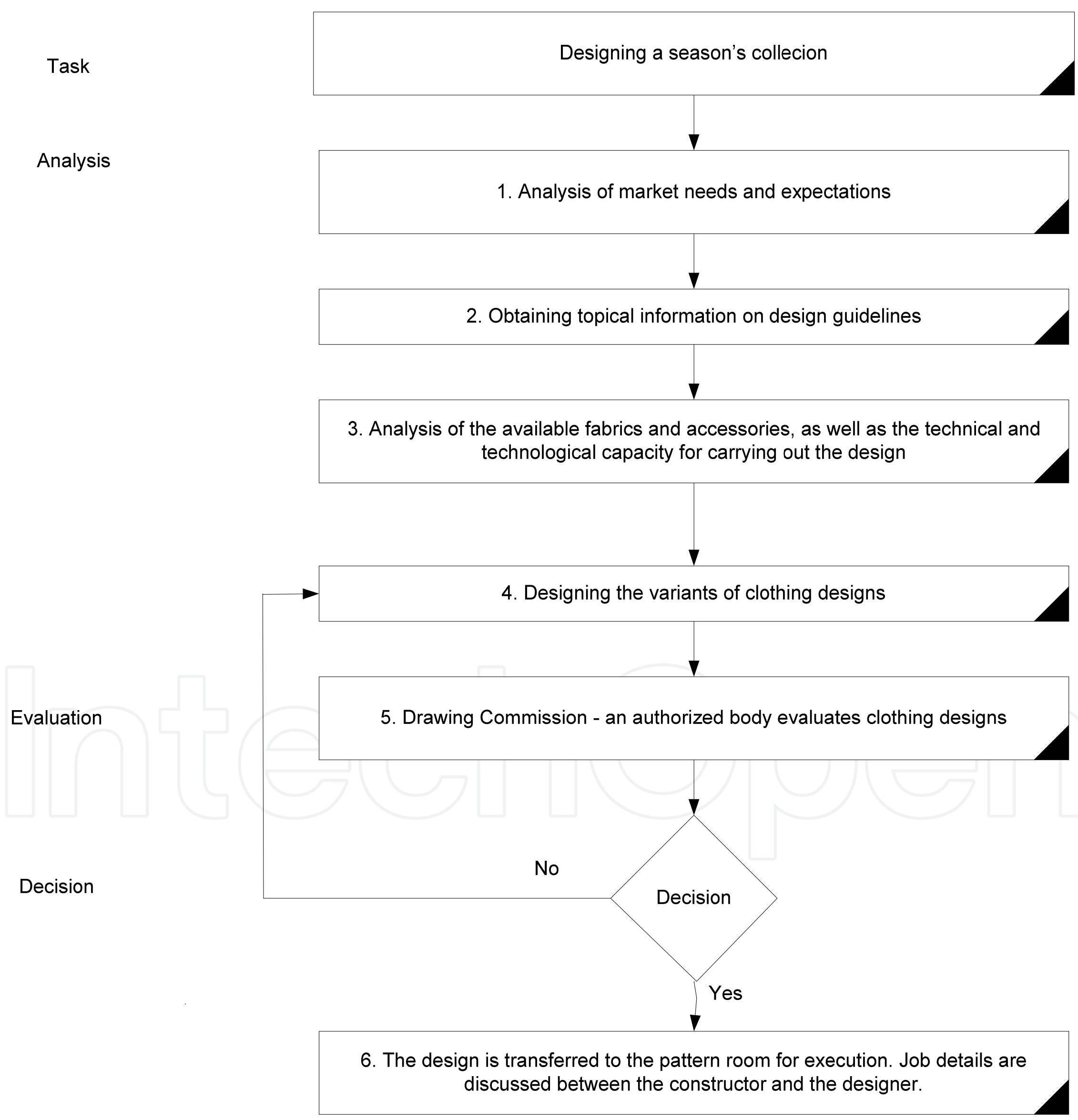

Diagram 1. An algorithm illustrating a fashion collection design process.
Source: developed by the author

Otherwise, the proposed models have to be redesigned. This procedure is repeated until the group of specialists appointed by the enterprise board decides that the outcomes are satisfactory (the number of designs meets the manufacturer's needs).

The Altshuller method applied to evaluate the results of all strings of events allowed scheduling the process correctly. The duration times of the strings were determined empirically and then verified using special catalogues being in possession of every clothing manufacturer. The actual duration times of identical actions may vary between particular manufacturers, as they operate in different technical and technological environments. Therefore, a production management model should follow from an investigation conducted in the concrete enterprise. Because process scheduling is widely discussed topic in the literature [2, 4], for the sake of keeping this article succinct we only wish to note that the schedule produced in the course of this investigation provided a basis for constructing a production management model.

The number of points for starting the model construction corresponded to the number of entry points to the process. The points are the leaves from which each branch consisting of many events (vertices) and of actions (edges) denoting their execution originates. The edges do not provide any information on their duration times, indicating only the sequence of events. At the next stage of tree development, particular branches converge to ultimately form the root, i.e. the final event. With these rules in mind, two assumptions were formulated to build the model:

- the start time of each string of actions depends on the process external and internal determinants,
- the duration of an action is a deterministic value expressed in terms of specific units.

Let us consider whether the second assumption is not a simplification possibly leading to the creation of an unrealistic model. We need to bear in mind that in the case of the short life-cycle goods the time for performing each elementary action can be allowed to deviate from the schedule only to a limited degree, because product selling must start at a predetermined point in time. Therefore, the deterministic time assumption actually relates to some expected time, the length of which is estimated based on long-time experience and many measurements. A starting point for future research could be the adaptation of the model to a situation where the elementary actions have non-deterministic (i.e. described by a random variable) execution times.

The production management model was built along the following lines:

1. Each process action is represented by an edge with a label indicating its duration.
2. There is one vertex for one intermediate state of the process. A vertex is a place where all edges symbolizing actions immediately preceding the state described by the vertex end and where an edge representing an action leading to the next state has its beginning.
3. The tree leaves are equivalent to the initial states of the strings of actions.
4. The root of the tree denotes that the process is complete and the product is ready.
5. Chronologically later process stages are closer to the root than the earlier stages, because the tree is oriented to the root.

6. Each vertex u can be assigned pairs of numbers p(u) and q(u) denoting the earliest and latest acceptable times of starting actions originating in the vertex.

Let us explain now the exact meanings of the notions and terms used in this article.

The earliest acceptable action start time p(u) is the time when the state u appears, assuming that the preceding actions were performed on schedule.

The latest acceptable action start time q(u) represented by an edge originating in the vertex u allows completing the entire process on schedule, provided that all the following actions are performed on time.

For each vertex u of the production management model, the following inequality exists:

$$p(u) \leq q(u) \quad (1)$$

If the strong inequality $p(u) < q(u)$ is met, then some extra time is available to the state u, which can be used to make up for any earlier delay in the string of actions. The acceptable length of this delay is given by q(u) – p(u) and it is not likely to affect the process completion time, unless the times of the next actions grow longer. However, if the equality q(u) = p(u) takes place, any delay in the string of actions preceding the state u may defer the process completion time. Therefore, the extra time r(u) available to the state u (i.e. the difference between the latest and earliest acceptable start times for an action) can be defined as:

$$r(u) = q(u) - p(u) \quad (2)$$

Based on the above, other assumptions can be formulated:

- if r(u) = 0, the state u will be called sensitive,
- if r(u) > 0, the state u will be called resistant.

To simplify the formulas, a state in the process represented by a vertex (e.g. u) will be treated as identical with that vertex, so the term state u will be used. Analogously, an action originating from the state u and having the state v as its end will be equated with the u–v edge and called the u–v action for the sake of clarity. The time of its execution will be denoted as t(u–v). These assumptions allow forming a production management model as a tree. Let us present its portion corresponding to the product creation subprocess (diagram 2).

The designer does his job (4), which is central to the design making subprocess, based on the leaves (actions 1, 2, 3 in diagram 1). The accepted drawings (5) are transferred to the sample room (6). At the same time, visually attractive fabrics are being sought, selected and purchased for the sample room (7−11). The fabrics and the prepared markers (12) are used for making the cutouts (13) that are then assembled with the accessories (14) to make a sample of the model (15). Parallel to that, the abridged model documentation is being prepared, so that the manufacturing costs can be calculated (16−20). The finished models are evaluated for their appearance and functionality (21). The accepted ones are priced and added to the fashion collection (22). If the production process were designed as part of B2B services involving the delivery of corporate clothing (employees meeting with customers shape their employer's image), then body measurements (23–26 in diagram 3) would precede the making of the markers.

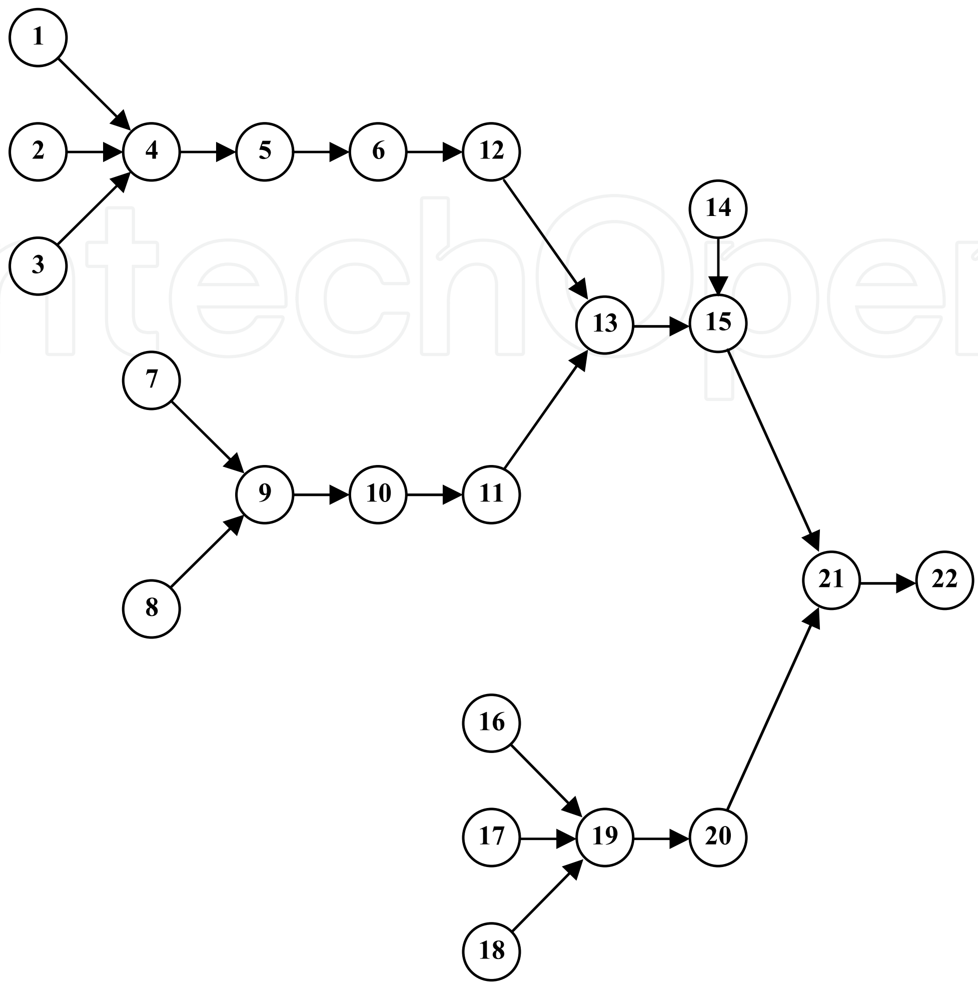

Diagram 2. A production management model – the product creation subprocess.
Source: developed by the author

The decisions giving the green light to the production of particular models (subsequent to consumer focus group, shows at fairs, etc.) initiate the following processes:

- market grading (27–31),
- delivery of the necessary materials (32–37),
- pattern making (38–41),
- preparation of the technical and technological documentation for the sewing room (42–46),
- operational planning (47–51),
- product manufacturing (52–60).

The discussed production management model is illustrated graphically in diagram 3, but without repeating the string of actions that has already been shown in diagram 2 (the product creation subprocess). Let us concentrate our discussion on the product manufacturing subprocess, which is determined by only several vertices. Therefore, the vertex 52 stands for assembling the „job order" (i.e. the putting together of all materials, accessories, the earlier made sample, and the technical and technological documentation for

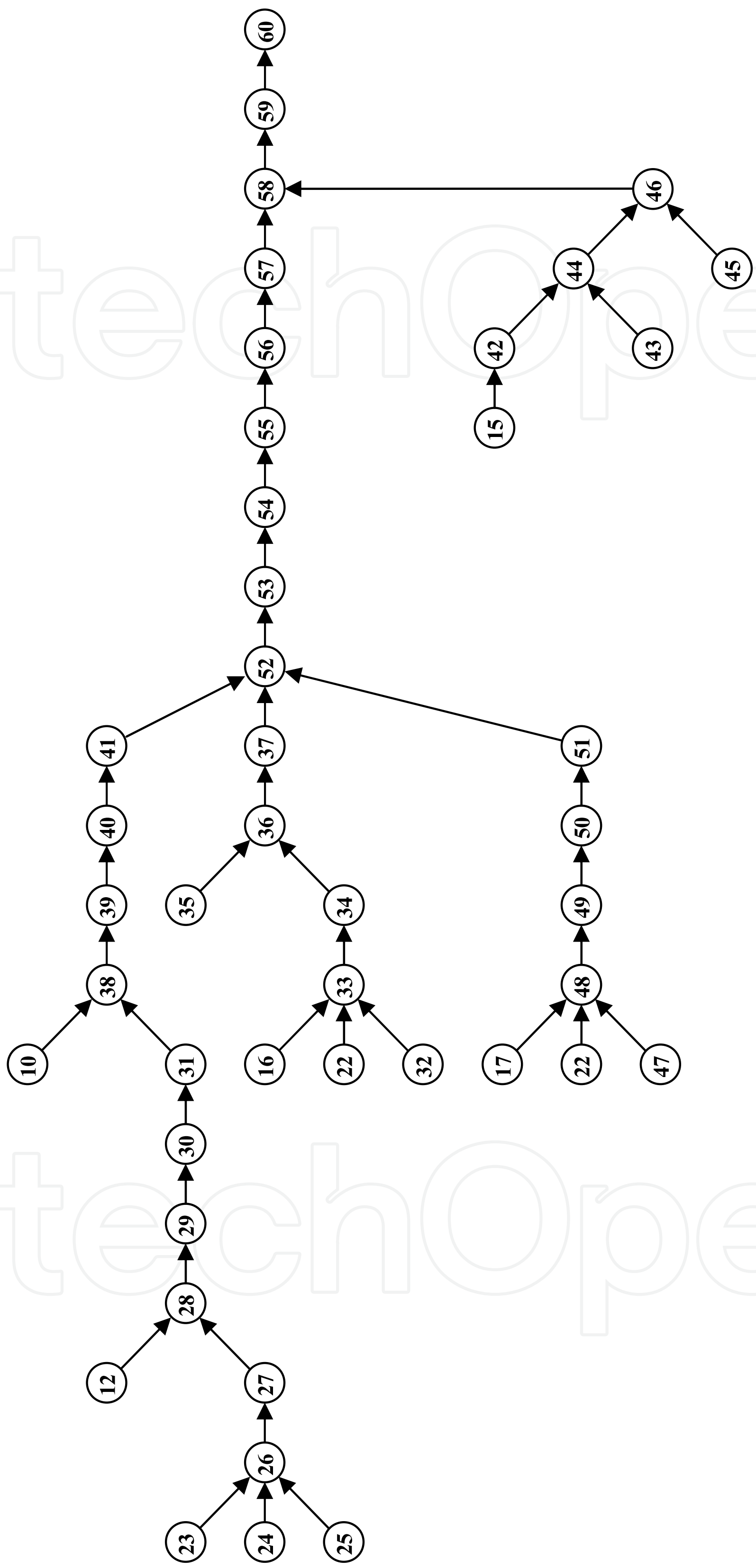

Diagram 3. The production management model.
Source: developed by the author

the manufacturing process), checking the order's completeness and then delivering the complete set to the manufacturing team. The vertices 53−57 represent the cutting room operations (spreading the fabric into stacks, dividing the stacked fabric into sections, making the patterns either automatically or manually, applying the stiffening inserts (if necessary), checking the cut-outs for quality and bundling them together into units of input delivered to the sewing room).

The cutouts and the technological documentation for their assembly meet at the vertex 58 being the string of operations performed in the sewing-room (the operations may vary depending on the model of clothing and the sewing room equipment). For instance, it takes several tens of operations to assemble the cutouts of an overcoat. Given that the construction of the product manufacturing subprocess has already been discussed in another original study by the author [13], it does not seem necessary to repeat it. The vertex 59 is the inspection of the finished product quality and the vertex 60 represents its delivery to the warehouse. Taking into account that the main goal of the investigation was to build a model of production management process, the aggregation of the elementary jobs into sub-processes seems rational.

5. A study of changes in the production process for short-life cycle goods

5.1 A critical path and an Indicator of Process Resistance in the production management model

The critical path of the tree determines the duration of the production process, in the same way as a network's critical path does. By identifying the critical path of the production management model and by calculating the Indicator of Process Resistance (IPR) to change the manager can estimate the degree to which the process completion date is at risk.

Let us present a procedure for finding a critical path or paths of the production management model that do not offer time reserves. Their number provides an indication of the process resistance to changes. The tree has at least one critical path, but every path running between an initial state and a final state can theoretically be a critical one. Then the production process is likely to end later than scheduled, because of changes increasing the duration of any of its constituent tasks. Production processes based on management models with a large number of critical paths are not resistant. The most resistant are processes having only one critical path. This shows that a production management model should be analysed while still being planned, as the range of the model verification options is the greatest then.

Let us present a procedure that was developed to identify the critical path of a production management model shaped as a rooted tree. Let the vertex w correspond to the tree's root (a final event of the production process). Among the states directly preceding the state w there is a state u having a time reserve $r(u) = 0$. If all states coming before the state w had time reserves, then the state w would have a time reserve too. This contradicts the assumption on which model [6] was founded, i.e.:

$$p(w) = q(w), \text{ i.e. } r(w) = 0 \tag{3}$$

Applying the same reasoning to the state u and its preceding states, we infer that there is some state v preceding the state u, for which $r(v) = 0$. This procedure should be repeated until we discover that a state without a time reserve is one of the initial states (let us call it the vertex *a*). The path starting at *a* and ending at *w* will be called a **critical path**. Accordingly, each state on the critical path is a critical state, particularly the initial state *a*.

While trying to identify the critical path we may discover that the analysed critical state *u* is preceded by more than one critical state. Then more than one critical path goes through the state *u*. This means that **the production management model (for the short life-cycle products)** has as many critical paths as critical initial states. Let us suppose that the model has *n* initial states containing *k* critical states. According to the earlier observations, the value of *k* is within the range:

$$1 \le k \le n \quad (4)$$

Consequently, the **Indicator of Process Resistance** to unexpected changes can be calculated as follows:

$$\text{IPR} = \frac{n-k}{n} = 1 - \frac{k}{n} \quad (5)$$

where: IPR – Indicator of Process Resistance to unexpected changes,
n– the number of the initial states (tree leaves),
k– the number of the critical states among the initial states.

IPR's extreme values are obtained for $k = n$ and $k = 1$. They define the range of values for the created indicator, i.e.:

$$< 0; 1 - \frac{1}{n} > \quad (6)$$

When every path in the production management model is critical, then $k = n$ and the IPR = 0. In the model with a single critical path $k = 1$ and the IPR is close to one, because it is calculated as:

$$\text{IPR} = 1 - \frac{1}{n} \approx 1 \quad (7)$$

It can be assumed that such defined **IPR's value measures the process resistance to changes that delay its completion.** The indicator can be used for assessing the production management model's design, as well as its actual performance (each time it has been modified). When the IPR is 0, then the timely completion of the production process is very much at risk, should any change extending the duration of any of its tasks occur. This means that the IPR is a synthetic measure of process resistance to changes, regardless of the stage they affect.

5.2 The PPCT as a method of investigating changes in the production process

A production management model (an inverted tree) provides information on the tasks, their duration and relationships. This aggregate knowledge allowed developing a method that:

- controls the duration of the process-related tasks,
- monitors changes affecting task duration,
- allows adjusting the model, when the changes delay the production process end date.

Let us present the **Production Process Control Tree** (PPCT) method, which was specifically developed for the short-life cycle goods. Let us note that the occurrence of some state *u* can be delayed with respect to the time p(*u*), because of one of two reasons:

- one of the states directly or indirectly preceding the state *u*, e.g. *a*, occurs later than p(*a*),
- one of the tasks preceding the state *u*, e.g. *a-u*, stretches over a longer period than the scheduled time t(*a-u*).

where: p(*u*) – the earliest moment of commencing the task originating in the vertex *u*,
p(*a*) – the earliest moment of commencing the task originating in the vertex *a*,
t(*a-u*) – the time for performing the task between the vertices *a* and *u*.

The delayed occurrence of the state *u* may make shift the production end to a later date. This is certain to happen, when *u* is a critical state. In a general case**, a delay will only take place when the delayed occurrence of the state *u* affects the commencement of the nearest critical state situated on the path linking the state *u* and the tree root**. However, the delay of the state *u* may also be "absorbed" by the time reserves of the states following *u*.

For the production management model to monitor changes, we need to find the times p(*u*) and q(*u*), representing the earliest moment of commencing each task and the latest moment of ending each task, respectively. According to the literature, the following rules can be applied to find the duration of the tasks:

- a deterministic rule for tasks carried out according to the company's own rules that explicitly prescribe task's deadline or duration,
- a probabilistic rule for tasks of duration determined empirically by an experienced expert.

The knowledge of the rules for determining the duration of tasks and time reserves played an important role in developing the PPCT method. Each time reserve indicates the length of time by which a task can extend without the production management model having to undergo adjustment. Considering that a production process is shaped by many variables, the constructed model has to be dynamic, enabling even some modifications to the schedule in case the end date of the production process becomes uncertain.

Let us suppose that we have a production management model shaped as an inverted tree. The duration of particular tasks and the moments when the initial states of tasks should start are also known. The duration of the task transforming the state *a* into *b* is denoted as t(*a*–*b*) and the earliest moment when the state *u* can commence is denoted as p(*u*). Let us create an algorithm for this production management model to find p(a_i), q(*w*) and q(*a*). The values will be used when the production management model will have to account for the impacts of variables affecting the production process. So:

- p(a_i) is the earliest allowed moment when the task originating in the vertex a_i should commence; it will be calculated according to formula (8) below,
- q(*w*) is the latest allowed moment of ending the final process activity *w*; it will be calculated according to formula (11) below,
- q(*a*) is the latest allowed time when the task originating in the vertex a should end; it will be calculated according to formula (13) below.

Let us use this method for calculating the time p(*u*) for the vertex *u*, which is not a tree leaf (i.e. an initial state). In the considered tree, the offspring of the vertex u are the vertices that come immediately before it. Then:

$$p(u) = \max \{p(a_i) + t(a_i–u)\} \quad \text{for } i = 1, \ldots, k \tag{8}$$

where: $p(u)$ – the earliest moment when the task originating in the vertex u should commence; $p(a_i)$ – the earliest moment when the task originating in the vertex a_i should commence, $t(a_i\text{-}u)$ – the duration of the task between the vertices a_i and u.

The above **rule helps to find the moments p(*u*), first for the states directly following the initial states and then recurrently for all vertices of the tree representing a production management model.**

Let w be a state equivalent to the tree root and $p(w)$ the actual end date of the production process. If T is the scheduled end date, then the process will end as planned when:

$$p(w) \le T \tag{9}$$

If otherwise, the product will not be ready on time. This problem can be handled by adjusting the process, which entails some restructuring of the production management model. Continuing the earlier procedure, we determine the moment $q(u)$, i.e. the latest allowed time when the state u should commence. Naturally, the relationship:

$$q(w) = T \tag{10}$$

still holds.

Building on the earlier assumption about the management of production of short life-cycle goods, we can write that:

$$\mathbf{p(w) = q(w) = T} \tag{11}$$

where: $p(w)$ – the earliest allowed moment when the task originating in the vertex w (the tree root) should commence,
$q(w)$ – the latest allowed when the task w, being the final task of the production process, should end,
T – the scheduled process end.

If the equality $p(w) = q(w) = T$ does not take place, then the condition (11) can be met by introducing a dummy state w and assuming that:

$$p(w') = T \text{ and } (w–w') = T – p(w) \tag{12}$$

The time $t(w–w')$ shows the shift in the product completion date, thus providing information on the observed change's effect on the production process. According to assumption (11), **the vertex *w* ending the production process (i.e. the tree root) is a critical state**. So, the moment $q(u)$ of the state u is determined and the state a precedes the state u towards the root. Then $q(a)$ can be defined using the following equation:

$$\mathbf{q(a) = q(u) – t(a–u)} \tag{13}$$

where: $q(a)$ – the latest allowed moment when the task originating in the vertex a preceding the vertex u should end,
$q(u)$ –the latest allowed moment when the task originating in the vertex u should end,
$t(a–u)$ – the duration of the task between the vertices a and u.

The value on the right hand-side of equation (13) is determined precisely, as there is only one edge that starts at a and ends at u. Consequently, the formula needs neither a minimum operator nor a maximum operator. The formula (13) allows recurrent determination of the time q(u) for each vertex of the tree, which property is utilised in the PPCT method to monitor changes.

Changing production circumstances may extend the amount of time that is needed to end the process. This threat must result in an immediate correction of the model data. In other words, changing circumstances should generate warnings about a possibly delayed product completion date.

The PPPCT method we propose for investigating production changes compares the duration of each task with its scheduled time. Let us assume that a task $a–x$ was performed in time t'($a–x$), which extended beyond its scheduled time t($a–x$) by n units. Then we have:

$$t'(a–x) = t(a–x) + n \quad (14)$$

Let us also assume that the path linking the state x and the tree root successively goes through the states y_1, y_2, …, y_k, so the path is given as $x – y_1 – …– y_k – w$. We additionally assume that all tasks preceding the state a were performed on time, meaning that the activity $a–x$ started at the moment p(a). Then, one of the three possibilities takes place:

$$1° \quad p(a) + t(a–x) + n \le p(x), \text{ or} \quad (15)$$

$$2° \quad p(x) < p(a) + t(a–x) + n \le q(x), \text{ or} \quad (16)$$

$$3° \quad q(x) < p(a) + t(a–x) + n. \quad (17)$$

where: p(x) – the earliest moment when the task originating in the vertex x should commence,
q(x) – the latest moment the task originating in the vertex x should end,
p(a) – the earliest moment when the task originating in the vertex a preceding the state x should commence
t($a–x$) – the duration of the task between the vertices a and x,
n – the number of units by which the duration of the task $a–x$ has been extended.

Let us explore now the meaning of the three situations and find the algorithms to deal with them.

Should the first case occur, the production process end date runs no risk of being delayed, because the earliest moment when the task y_1 (initiation of the activity x) should start takes place after the length of time allocated to activity $a–x$ elapses. So the model of the process does not need any modifications, but replacing the time t($a–x$) by t'($a–x$) = t($a–x$) + n. In this case, the production manager does not have to be informed about an event if occurred, as its influence was neutral.

In the second case, the production process is not exposed to any direct threat to its timely completion, because the state x has the time reserve r(x) = q(x) – p(x). The task $a–x$ will end not later than q(x), being the latest allowed moment for the task $x––y_1$ to commence. In this situation, the tree requires the following modifications:

i. the time ($a–x$) has to be replaced with t'($a–x$) = t($a–x$) + n,

ii. each state on the path $x - y_1 - \ldots - y_k - w$ has to be assigned a new commencement time using the formula (8) and some obvious changes have to be made to the formula symbols (u has to be replaced with the right vertex name and a_i with its preceding vertices).

The production manager has to be notified of the changes, but no action is required to prevent the production process from running late.

Two things need to be raised at this point: 1) the moments p(x), p(y_1), p(y_2), …, p(y_k) have to be recalculated, because the changes may have transformed the resistant states into critical ones, thus affecting the process structure; 2) the moments q(x), q(y_1), q(y_2), …, q(y_k) do not change, because the scheduled process end date T = p(w) = q(w) that depends on them remains the same.

In the third case, the production process end date will be exceeded, because the state x needs more time to end than its time reserve r(x) allows. Hence, the model has to be modified as follows:

i. the time t(a–x) has to be replaced with t'(a–x) = t(a–x) + n,
ii. each state on the path $x - y_1 - \ldots - y_k - w$ has to be assigned a new commencement time using the formula (8) and some obvious changes have to be made to the formula symbols (u has to be replaced with the right vertex name and a_i with its preceding vertices),
iii. the process end date T has to be replaced with T′ = p(w), assuming at the same time that q(w) = p(w), where the time p(w) represents a new process end date calculated at step (ii),
iv. now the latest allowed moments of starting tasks that have not been carried out yet have to be determined, their duration of the tasks remaining the same.

The steps (i) ÷ (iv) **readjust the model of the process**. The production manager has to be notified of the situation to decide about the next steps after analysing the new model. The manager may choose to shorten the sequence of activities $x - y_1 - \ldots - y_k - w$ by introducing organizational, technical or technological improvements. If the intervention is effective and, for instance, the time t($y_i - y_{i+1}$) becomes shorter by m units, then the steps (i) ÷ (iv) should be repeated, with the time t($y_i - y_{i+1}$) at step (i) being replaced by t($y_i - y_{i+1}$) – m.

Because decisions on taking actions causing dynamic adjustment of the model usually increase product manufacturing costs, the company board has to grant the production manager an appropriate scope of authority. Otherwise, the PPCT method enabling interactive management of production processes will not be as effective as it can be. If the duration of the longest path of the tree ensures following the intervention that the production process will end as scheduled, then the process is continued. If otherwise, the production manager has to notify the Board (or another relevant body) of the situation, which may choose to discontinue the production process (after estimating the losses) or to carry on.

6. Conclusion

The presented operational algorithm allows concluding that the empirical verification of the production model for the short life cycle products confirms the hypothesis of the determined duration of the production process. The process consists of four subprocesses that run cyclically and are staggered with respect to each other by constant time intervals. Because the main building material of the management science is the inductive methods that enable drawing general conclusions from empirical research [22], the presented modelling results can be assumed to have a scientific value. The generated model of the product manufacturing cycle is central to company management. Its importance goes beyond the possibility of synchronising the subprocesses alone. The prolonged production of the SLCP shortens the available selling period, and in the extreme case it can completely ruin the sales. This situation is caused by the seasonal character of sales, the time of the year when a clothing article can be worn, etc.

A production management model based on an inverted tree concept (graph theory) allows an innovative, graphical representation of a management process applied to the production of short life-cycle goods. Although an inverted rooted tree has not been used in management theory so far, there are good reasons for constructing it, because it can help:

- identify the sensitive graph routes, i.e. those determining process duration,
- develop a unique measure of process resistance to change (PRI) enabling an immediate evaluation of the production management model for the designed production process or after each process modification caused by changes arising during its execution,
- develop a method for analysing changes in the management of production of short life-cycle goods that allows its user to have active control over the process.

The amount of material discussing the above issues is quite extensive, so it will be presented in other articles that will be published in this periodical.

All computations (necessary to design the original tree, to determine its longest path and to readjust the production management model) can be performed in real time, once an appropriate computer software has been developed. The need for the management process to integrate technology, organizational issues and IT, regardless of the supervisory, stimulating role of the process manager, was accentuated by B. Nogalski [20]. The software should be built around the aforementioned algorithm that enables study of changes in the production of the short life-cycle goods. The software helps implement the method we propose in business practice. Making decisions under the pressure of time is a key problem that companies manufacturing short life-cycle products have to resolve. Modern production management methods, including the PPCT, combined with IT tools are the only ones that make it possible to:

- analyse a production process and its changing circumstances on an on-going basis,
- make decisions in real time to offset the negative impacts of changing process circumstances,
- minimize the losses a company may incur should it decide to discontinue the production process, because every step forwards generates unnecessary costs (augmenting the losses).

The proposed method for analysing changes in the production process can improve the effectiveness of companies making short life-cycle goods that function in turbulent environments. According to the *Global Trends 2025* report prepared by the National Intelligence Council, such environments are becoming the norm today [21]. The report reveals not only problems, but also opportunities that arise from unexpected changes creating new economic realities.

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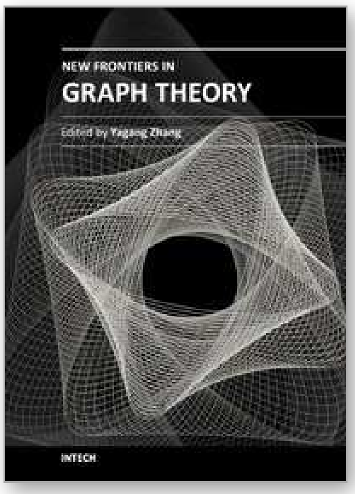

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Nowadays, graph theory is an important analysis tool in mathematics and computer science. Because of the inherent simplicity of graph theory, it can be used to model many different physical and abstract systems such as transportation and communication networks, models for business administration, political science, and psychology and so on. The purpose of this book is not only to present the latest state and development tendencies of graph theory, but to bring the reader far enough along the way to enable him to embark on the research problems of his own. Taking into account the large amount of knowledge about graph theory and practice presented in the book, it has two major parts: theoretical researches and applications. The book is also intended for both graduate and postgraduate students in fields such as mathematics, computer science, system sciences, biology, engineering, cybernetics, and social sciences, and as a reference for software professionals and practitioners.