Design Methodology for Automatic Assembly

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Abstract: Efficient design methods are becoming increasingly necessary, in order to design, both product and production, better and faster. In view to this, the following questions are paramount: how can we increase the controllability of the design process and how can we realize a high design quality? This paper focuses on this subject, with applications to automatic assembly.

Keywords: Design process, concurrent engineering, DFA, assembly automation, robotic assembly

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1. Introduction

An efficient design process is characterized by a cyclic course of reasoning, in which objective and means, problem and solution are studied in their interaction. The design process should be structured concentrically, with a parallel and continual iterative interaction between product, process, and system design. The literature on design contains a number of models of the design process, each of which highlights a certain aspect of this process from a different point of view, (Pahl and Beitz 1984), (Hubka and Eder 1988), and (Nevins and Whitney 1989). The concentric nature of the design reasoning is not explicitly presented in these design models. Against this background, a concentric design model is introduced in this paper, based on the conceptual design of robotic assembly systems, in conjunction with the analysis and optimization of the product and process design. The starting point in this model is the development of new assembly systems, based on an existing product idea.

2.Starting Point in Designing Production Systems

The design process is defined as *the process in which the wishes of customers are translated into prescriptions for the shape and use of systems.* Before going more deeply into the design process, some concepts of the system theory are first discussed in brief. We need these concepts to regard the product, assembly process and assembly system, as well as the interrelationships between them, as a system and to study them as such. This collection of concepts forms the starting point in the analysis and design of production systems.

According to the system theory, *a system is a collection of elements each of which has certain properties*; these can be either of a physical or of a geometric nature. *The value of these properties at a specific moment in the system is the state of the system.* When the state of the system changes, this is called an *event.* Between the elements in the system, *relationships exist*, which describe a certain cohesion between those elements. The enumeration of these relationships is the *structure of the system*. A distinction can also be made between *subsystems* and *aspect systems*, in order to gain a better insight into complex systems. A subsystem is a subset of elements in a system, in which all original relationships between these elements remain unchanged. An aspect system is a subset of relationships in the system, in which all elements remain unchanged. Furthermore, a distinction is made between *static systems* and *dynamic systems*. In static systems, contrary to dynamic systems, no events take place. Central to this article is the design of robotic assembly systems. These systems are dynamic (when they are in operation), because an assembly process occurs which is carried out by means of a collection of subsystems, which each fulfils its own function within that process. Under influence of this process, the assembly system demonstrates a certain *behaviour*. This behaviour is the manner in which the system reacts to certain internal and external changes. A *process* is defined as *a series of transformations in the course of the throughput, as a result of which the input elements undergo a change in regard to their place, position, size, shape, function, property, or any other characteristic*.

Owing to the presence of the process, *permanent* and *temporary elements* can be distinguished in the assembly system. The permanent elements are the subsystems or components of the assembly system, such as feeding systems, robots and sensors. These subsystems fulfil functions in the assembly process, and form, through mutual relationships, the structure of the system. The temporary elements are continuously imported into the assembly system and transformed into an output desired by the environment (market). These elements entail a *flow of material* (product parts), an *energy flow* and an *information flow* (see Figure 1). In this article, the emphasis lies on the flow of material. Hence, only the flow of material is considered in regard to the output (Figure 1).

The assembly process consists of a series of assembly operations (feeding, handling, composing, checking, adjusting and special processes), which can each be divided into sub-operations. An assembly system in operation thus generates *a series of these singular operations, which are interconnected by means of a structure of interactions and which aim at bringing together product parts, to form composite units.*

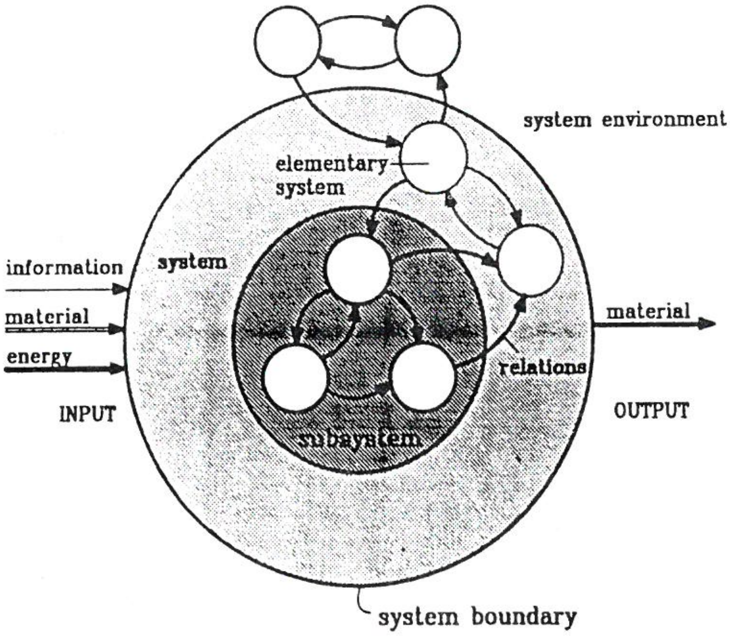

Figure 1. Representation of a Dynamic System

The assembly system fulfils its function in its environment by means of the assembly process, which consists of assembling product parts into final composites which are required by the market. The system environment is defined as *those elements outside the system, which influence the process within the system or influence the properties of the system elements, or, vice versa, are influenced by the system.* The system objective is to fulfil the system function in the environment. To realize this objective it is necessary that the course of the assembly process is controllable. Thus, in the assembly process, *measuring functions, controlling functions and supporting functions* must be fulfilled besides *transformation functions.* The supporting functions are usually fulfilled by people and in robotic assembly systems they can generally be divided into: system set-up, stocking of feeding systems, programming, rectifying malfunctions, and maintenance. In view of the above, it can be said that a robotic assembly system is *a collection of subsystems, comprising people, one or more assembly robots and flexible peripheral equipment, which are structured through relationships among these subsystems* (Rampersad, 1994a). Figure 2 shows an example of a robotic assembly system which consists of one robot and several peripheral units.

A sharp distinction between *function* and *task of an element* is also important. The function of an element is *that which is caused by the element and which is required by the larger whole.* The task of an element is *that which must be done so that the function should be fulfilled.* The task, therefore, involves the activities in the system, while the function which relates to the desired result, involves the consequences of these activities for the environment (the intention) of the system. The function of *the assembly system is the assembly of product parts into final composites which are required by the environment.* This function is dictated by the market, and results in production characteristics such as production volumes and batch sizes. The task of the assembly system is to execute assembly operations, in order to fulfil the system function. When designing production systems, it is sensible, because of the complexity of these systems, to distinguish between function and task, since this enables us to think about the system function, without taking into account the manner in which this is fulfilled. Furthermore, in the design process a number of alternative solutions is generated for the manner who the function is to be fulfilled. This benefits the design quality and the controllability of the design process. More and more, therefore, system design is focussing on functions instead of tasks. Because production systems are generally complex, it is recommended that these two concepts (function and task) be considered as separate design variables.

The concepts mentioned, form the starting point in the model approach of both the transformation process and the design process.

3. Transformation Model

The transformation process entails a series of assembly operations, which cause the properties and the state of the input materials to change. The properties of the input materials are determined by the product assortment, the product structure and the product components (Rampersad, 1995a). The state of the input materials is determined by the circumstance (condition) in which the product finds itself. Figure 3 gives an outline of the process of change of both property and state, by which input materials, energy and information can be

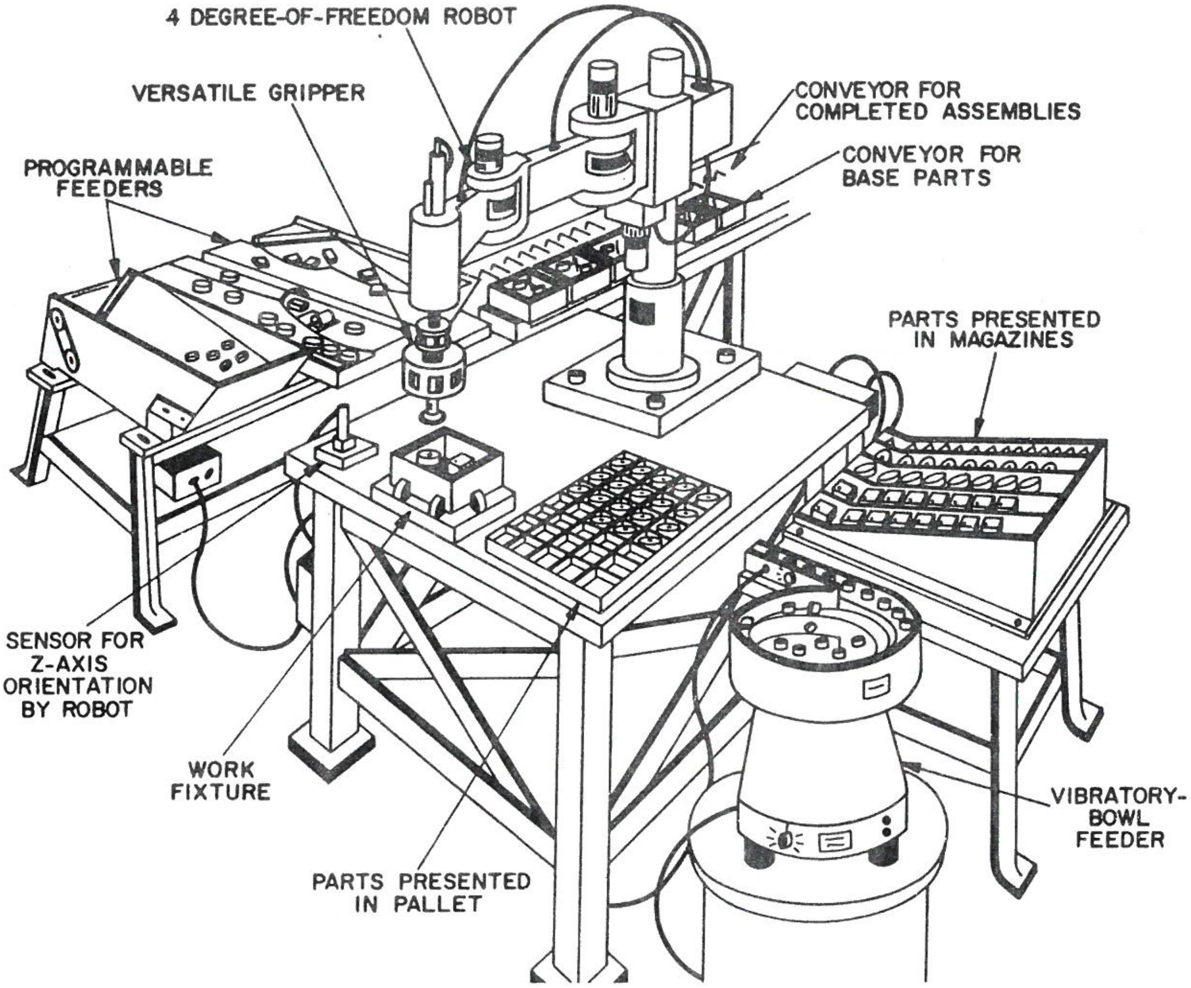

Figure 2. An Example of a Robotic Assembly System (Boothroyd, 1992)

transformed into output products desired by the environment.

The system function is fulfilled by *the change of the properties of the input materials Y_i (before the transformation process) to the properties of the output product Y_o (at the completion of the process). The system task is effected by the execution of the assembly operations, causing the system function to be fulfilled, in which the initial state of the input materials S_i at time t_1 is transformed into the state of the output product S_o at time t_2.* The output state S_o of the product thus originates from the input state S_i under the influence of process conditions. As a consequence of this change of state (ΔS), the properties of the input materials Y_i are transferred to the properties of the output product Y_o. The required change of state ΔS strongly affects the assembly time (t_2 - t_1) and therefore also the assembly volume (number of assembled composites per time unit), which is expressed in the system performance (Rampersad, 1995b). In the following chapter the model approach of the design process will be discussed.

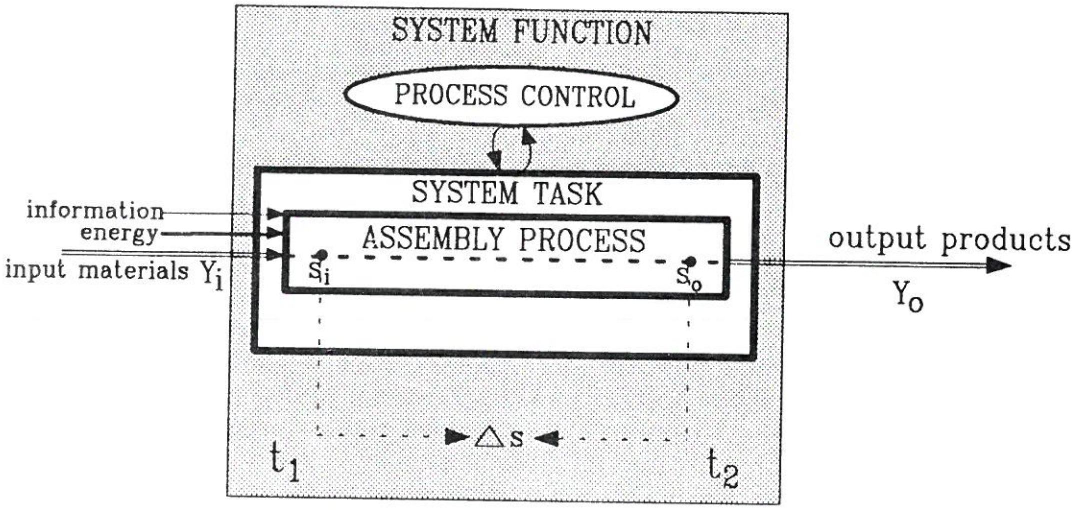

Figure 3. Process of Change of Both Property and State

4. Model Approach of the Design Process

In the design process it is important to base one's reasoning on the objective, and then, via function, task, properties, state and structure, to reach the shape of the system. Figure 4 shows a model of this design process. This model has a series of arrows which cross one another in the transformation process. The horizontal series concerns *the product in the process of assembling and the vertical series concern the system in the process of designing*. The arrows indicate the flow of information in the design process. The system design process distinguishes five sequential steps: *analysis, system synthesis, system simulation, system evaluation and decision*. The design steps are shown in the Figure by means of double-outlined boxes. The analysis step entails the analysis of the product, process and production characteristics, and, based on those, the definition of the system function. This results in a list of requirements called 'system properties'. The elements 'system properties', 'system structure', and 'system layout' are in turn the result of a design activity. Figure 4 shows that the design cycle is followed many times. Design is, *after all, an iterative process.*

The various design stages in the model will be described in brief, after that a design model will be introduced in which the concentric course of the design process and the iterative nature of the design reasoning will be presented explicitly.

Analysis

The analysis step involves the analysis of the product, process and production characteristics and, hence, the definition of the system function and the system task. The system function forms the point of departure in the design of assembly systems. This function involves the assembly of product parts into final composites required by the environment. The fulfilment of the system function in the environment is the system objective. The requirements of the environment are generally based on market research. This finds expression in the *product diversity, product volumes, batch sizes and expectations regarding changes of the product properties* and the related process properties during the life time of the system. To realize the system objective the system will have to perform its task by means of efficient execution of the assembly operations. To be able to perform these operations optimally, the product properties must be analysed in conjunction with the analysis of the process and production characteristics (see Figure 4). To this end, a coherent DFA procedure has been developed: the so-called DFA house (Rampersad, 1993). This design stage usually results in the re-design of both the product and the related assembly process (Boothroyd, 1992). Central to this, are avoidance and simplification of assembly operations, as well as the development of an optimum assembly structure. The simplified assembly operations concur with the system task to be carried out.

System properties

The formulation of the *system properties* is an elaboration of the *system objective*. For the realization of the system objective it is necessary that the input materials, the process and the system have such properties that the desired result (output) is achieved at minimal costs (input). The system must therefore have the correct combination of properties to be able to execute the assembly operations. These properties form the *criteria* which the principle solution to be designed, should meet (desired system properties). The desired system properties are usually laid down in a *list of requirements*. This list comprises criteria which are starting points for both the system synthesis and for the assessment of the extent to which the design meets its objective. Since a principle solution determines the design of the system only in part, the properties in this design stage are not complete; at this conceptual design stage, a principle solution has materialized so far that the technical and physical functioning of the system can be assessed in general.

System synthesis

System synthesis entails *the composition of a new system from (partially) known components*. This step involves the generation of a conceptual design of the system. In order to develop

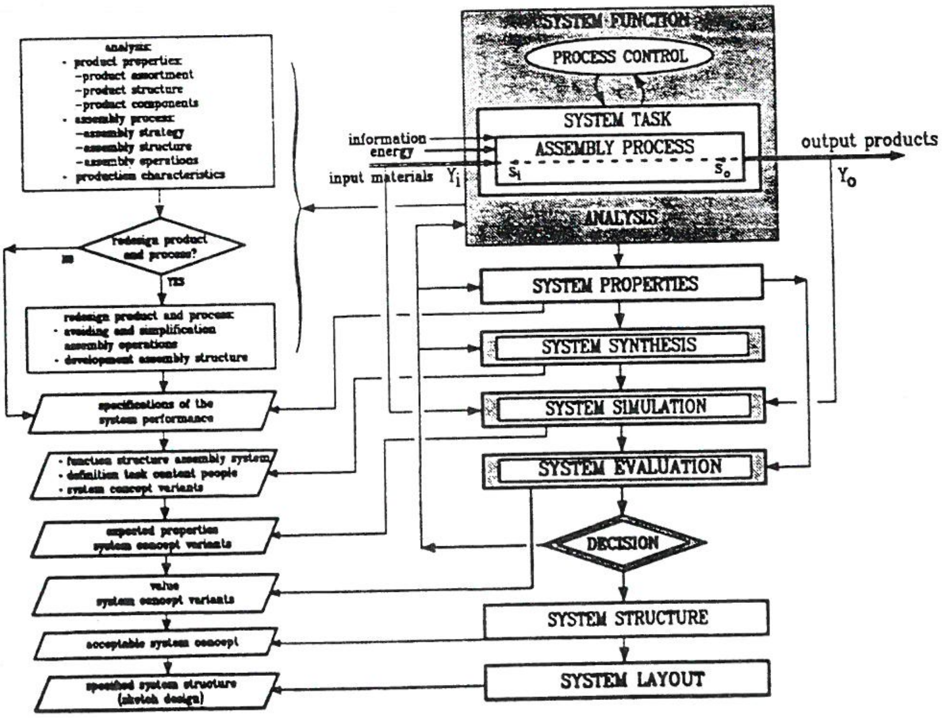

Figure 4. Model of the Design Process

conceptual solutions, a combination of *function analysis* and *morphology* can be used, (Rampersad, 1994b). Function analysis is a systematic method for the analysis and development of a *function structure*. The function structure entails the functions in the system and the relationships between these functions. It indicates what sub-functions should be realized by the system components in order to fulfil the system function. The relationships between the sub-functions are determined in particular by cohesion of the process. In this synthesis step the assembly structure is considered to be the starting point for the description of the assembly system as a cohesive whole of sub-functions. The next step of this synthesis is to conceive concrete system components for each sub-function, by means of the morphological method. This method aims at finding all theoretically possible solutions per sub-function on the basis of a morphological chart. This chart is composed of functions (parameters) and system components thereby these functions can be fulfilled. Ordering the different system components per sub-function, based on the proper assembly strategy, leads to alternative system structures. Expertise and creativity play an important role in this design stage.

System simulation

This design step entails the analysis of the performance of alternative system structures. Thus, the properties and the behaviour of these design alternatives are assessed. Simulation is indispensable here. This leads to expectations concerning the (actual) properties of the system structures, (Drimmelen et al. 1994) and (Rampersad 1994c).

System evaluation

This design step involves the determination of the value of the concept variants. To this end, the expected system properties (from the preceding step) are compared with the desired system properties. The differences between these two sets of properties, will have to lead to the decision on whether the design alternative is acceptable or not.

Decision

The system evaluation can lead to the decision to elaborate the best system concept, to make a new system design or to review the design. This design step indicates that the development of the system concept is an iterative process. For this, the step allows feedback to be given to 'system synthesis', 'system properties' and 'analysis', in order to optimize the design alternative and to adjust or expand the system properties (see Figure 4). The feedback to the analysis step might result in the review of the assembly method: possibly manual assembly or mechanized assembly instead of robotic assembly.

System structure

The selected system structure is the final acceptable system concept which can be developed further. It is the framework of the physical assembly system, providing a general outline of how the various subsystems are related to one another through the flow of material.

System layout

The system layout entails an arranged positioning of concrete system components in the space within the system. It is an elaboration of the selected system structure in the form of a sketched design. The location of each system component within the assembly system is determined in detail. Simulation can also be useful in this design stage for further analysis of the system behaviour (cycle times, reach of positions, as well as collision between robot and peripheral equipment), and, hence, the optimization of the conceptual system layout.

5. A Concentric Design Model

The design process of Figure 4 has resulted in the development of a concentric design model (see Figure 5). Each level on the product, process, and system axes must be completed before a following, lower level can be started. On the axis of the assembly system only one design activity is assumed at a time. This design activity is elaborated in conjunction with one or more levels of complexity, with regard to the product and process characteristics. The spiral clearly shows the cyclic and iterative nature of the design process, as well as its parallel and simultaneous course. The starting point of the concentric design model is the development of a new assembly system, based on an existing product idea. Figure 5 shows that certain product and process variables should first be analysed and possibly optimized before a design activity can be initiated on the system axis. Although the delineation of the design process in this paper lies with the conceptual system design, the whole system development trajectory has, for the sake of completeness, been given in Figure 5. This trajectory has been divided into various stages, so that after a number of stages a decision must be made on the continuation of the design project. In the conceptual trajectory, one decision point has been inserted, while various decision points are possible in the ensuing development trajectory.

Explanation of the concentric design model

First, the system function is defined on the basis of market research, in which the system objectives are specified. Parallel to this, the properties of the product and the assembly process are analysed, followed by the analysis of the production characteristics. After a possible re-design of the product and the assembly process, the system task and the system properties are defined. This design activity is followed by the development of the function structure. The function structure indicates which subfunctions should be realized by the system components in order to fulfil the system function. To develop the function structure, it is necessary to further analyse the product structure and hence to develop the assembly structure. The next step consists in the selection of system components after the product components and the product assortment have been analysed, the assembly strategy has been determined and also the assembly operations have been analysed. The assembly strategy involves the choices which are made among alternative methods, to increase the controllability of the assembly process (Rampersad 1994a). For example, the product assortment strongly affects the method of feeding, transporting, and grasping. The assembly strategy entails also the choice of line balancing, the choice of a line or cell concept, and the choice of the assembly method (manual, mechanized, or robotic assembly). The task content for the operators should also be defined at this design stage. After this design stage, the alternative system structures must be developed, followed by simulation and evaluation of the different design alternatives. On the basis of the system evaluation, the decision must be made whether to elaborate the selected system structure, to make a new design, or to re-design it. The feedback to the different stages in the design process is marked with thin arrows on the assembly system axis. The next step entails the development of the conceptual system layout, after the product assortment has been re-analysed and the assembly strategy has been determined.

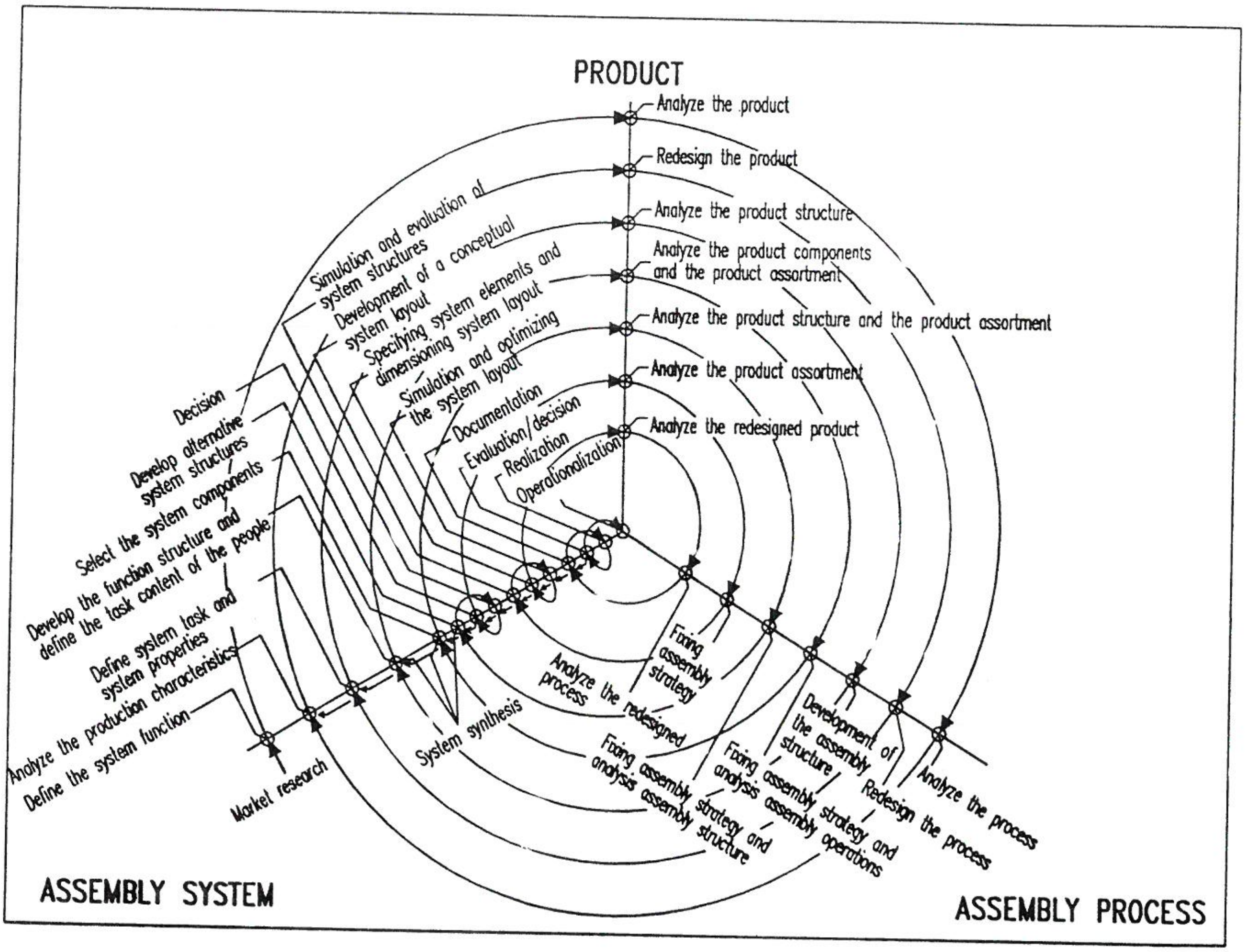

Figure 5. Model of the Concentric Design Process

The conceptual system layout should then be simulated and if necessary and possible, optimized. The following design step consists of the determination of the functional element specifications and of the detailed dimensions of the system layout. The definition of the information- flows in the system and the design of the system control also form part of this design step. It is also important to document on the development of the system continuously during the design process. Apart from the system variables, the product and process variables should also be included in the document. A re-analysis of the (re-designed) product and process is therefore required. Before the system realization, it is furthermore necessary to evaluate the business economic aspect (cost-benefit analysis) in detail. The realization stage is generally distributed over a number of sub-stages, namely: system implementation, programming, system integration in the entire production, testing of the system, and training of the relevant personnel. On the basis of the system test, it can

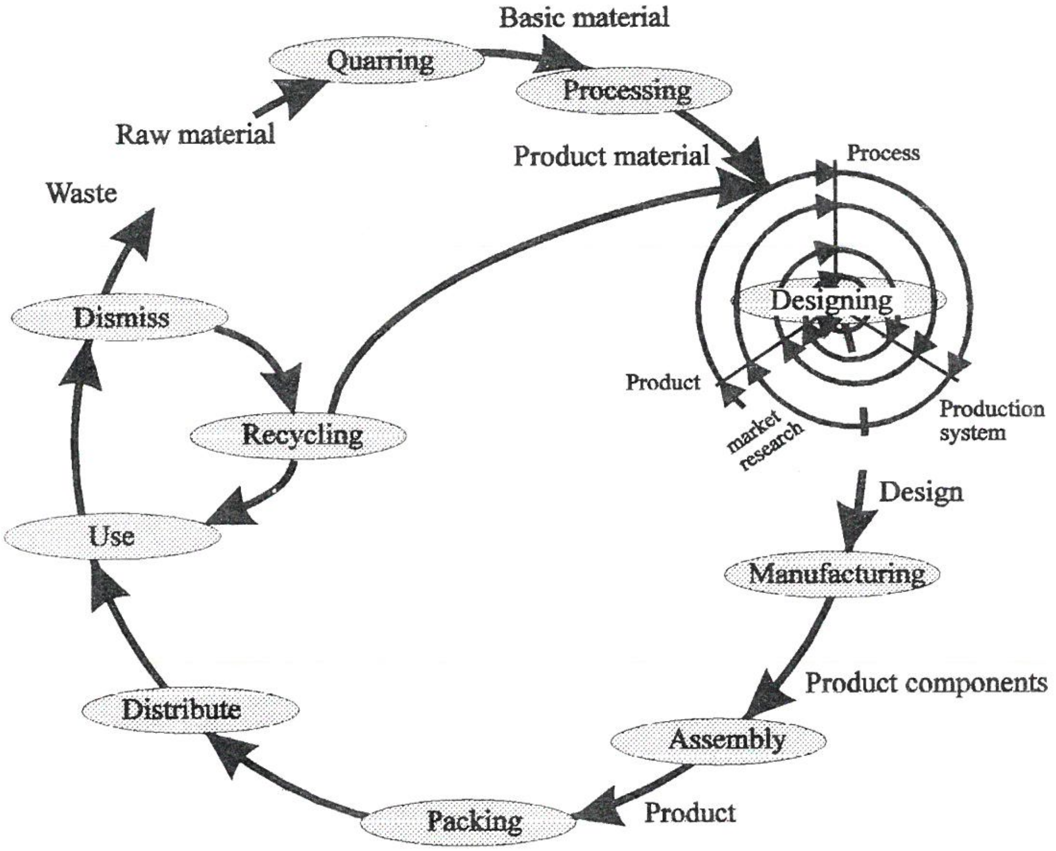

Figure 6. Concentric Design Processa as Part of the Product Chain

be decided whether or not to optimize the system. The last step in the system development process concerns the operationalization. This entails putting the system into operation and maintaining it.

Figure 6 shows the concentric design process as part of the total product chain, from raw-material until waste and recycling. In order to design durable production systems the designer should also think well of other transformation processes in this chain. For a further explanation of the design process, (Rampersad 1994a).

6. Concluding Remarks

The contribution of this paper is the introduction of a concentric design model, which offers the opportunity to increase the controllability of the design process. This can be realized whenever the design process is carried out in a systematic and structured manner, in conjunction with a parallel and iterative interaction between product, process and system design. The design model also provides the opportunity to encourage the designer in thinking well of the product and process design before a system design activity starts.

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