İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

USE OF MECHATRONICS APPROACH IN PRODUCT AND PROCESS DESIGN

M.Sc. Thesis by

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Department : Management Engineering

Programme: Management Engineering

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

ÜRÜN VE SÜREÇ TASARIMINDA MEKATRONİK UYGULAMALAR

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ÖNSÖZ

Yaklaşık olarak üç buçuk senelik bir sürenin ardından ortaya koyabildiğim bu tez çalışmasını kendi kişisel gelişimime yapmış olduğu katkının yanında bilim literatürüne de katkıda bulunması dileğiyle yazıya dökmüş buluyorum. Kendimce çok ciddi bir emek sarf ederek ortaya koyabildiğim bu tezin yalnızca önsözünü ve küçük bir özetini değil tamamını Türkçe olarak yazmak isterdim. Ancak, gerek bu tez çalışmasını yürüttüğüm esnada gerekse sekiz yılı aşkın üniversite öğrenimim süresince sıkça başvurduğum, çok farklı milletlerden yazarların kaleminden çıkmış bilimsel makaleleri göz önüne aldığımda, uluslararası kullanıma açık olması adına tezimi İngilizce olarak yazmış olmanın doğru bir karar olduğunu zannediyorum.

Yapmış olduğum bu çalışma vesilesiyle, yalnızca bu tez çalışmam süresince değil şu ana kadar 20 yılı bulan tüm eğitim hayatım boyunca benden desteklerini hiç eksik etmeyen aileme sonsuz minnetlerimi sunuyorum. Ayrıca tez çalışmam boyunca her zaman yanımda olan ve katkılarıyla tezimi şekillendirip bir sonuca vardırmamda bana ciddi yardımlarda bulunan saygıdeğer hocam Dr. Halefşan Sümen'e çok ama çok teşekkürler ediyorum. Diğer taraftan halen mensubu olduğum ve tezimin uygulama kısmındaki çalışmaya kaynak oluşturan, ülkemizin sektöründe öncü ve dünya çapında güçlü bir özel sektör kuruluşu olan Arçelik AŞ.'ye de teşekkürü bir borç bilirim. Son olarak, hayatımın en değerli dönemlerinden birini bir mensubu olmaktan büyük bir gurur duyarak geçirdiğim, kişisel gelişimimde paha biçilmez bir paya sahip olan ve bu tezle birlikte üçüncü diplomasını alacak olduğum İstanbul Teknik Üniversitesi'ne bir kurum olarak ve tek tüm mensuplarına en derin saygı ve sonsuz minnetlerimi sunarım.

Murat Sevindik

Ocak 2007

CONTENTS

SHORT FORMS

AC	: Alternating Current
CAD	: Computer Aided Design
CNC	: Computer Numerical Control
CTO	: Chief Technology Officer
DC	: Direct Current
NC	: Numerical Control
MEs	: Mechatronics Engineers

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ÜRÜN VE SÜREÇ TASARIMINDA MEKATRONİK UYGULAMALAR

(ÖZET)

Günlük hayatımızda edindiği yer ve önemi giderek artan mekatronik uygulamaların ürün ve süreç tasarımındaki yerinin incelendiği bu çalışmada, öncelikle 1960'lı yıllarda Japon Yasakawa Electric Company'nin isim babalığını yaparak literatüre kazandırdığı mekatronik kelimesine yüklenen anlamlar, kelimenin tanımı ve ifade etmeye çalıştığı uygulamaların tarihsel gelişimi incelenmiştir. Yapılan değerlendirmelerin sonucunda mekatroniğin tanımı şu şekilde yapılmıştır: Mekatronik; mekanik, elektrik, kontrol ve yazılım uygulamalarını bütünleşik ve sinerjik bir entegrasyon halinde, ortaya koyduğu çözümün ayrılmaz bir parçası olarak içinde barındıran ürün ve süreçlerin tasarımı ve üretimi metodolojisidir.

Çalışmanın devamında mekatronik uygulamaları doğuracak şekilde, tasarım metodolojilerinde görülen evrim incelenmiş ve mekatronik uygulamaların diğer uygulamalara (elektromekanik ya da tek disiplinli uygulamalar) kıyasla üstünlükleri dile getirilmiştir. Daha sonra mühendislik tasarım metodolojisi detaylarıyla incelenmiş ve gerçek manada mekatronik ürün ve süreçleri ortaya koyabilecek bir tasarım metodolojisinin nasıl olması gerektiği sorgulanmıştır. Bu kapsamda ilk olarak mekatronik mühendislerinin tasarım sürecinde yer almalarının önemi ve tasarım sürecine katkılarının neler olacağı açıklanmış ve bu faaliyetleri yerine getirecek olan mekatronik mühendislerin karakteristikleri ortaya konmuştur. Buna göre ileri sürülerek açıklaması yapılan ilk sonuç şudur: Gerçek manada mekatronik bir ürün ya da prosesin tasarımı için tasarım ekibinin tamamen mekatronik mühendislerinden oluşması yada en azından mekatronik mühendisleri içermesi gerekmektedir. Bu mekatronik mühendisleri de multi-disipliner bir eğitime sahip olmalı; ilgili tüm mühendislik birimlerinin kısıtlarını, önceliklerini, güçlü ve zayıf yönlerini bilmeli; ilgili her bir disipline ilişkin jargona hâkim olmalı ve pazarlama, finansman, satış gibi birimlerin dilinden de anlayabilmeli; başarılı müzakerelerle çatışmayı yenebilmeli ve tek yönlü bakıştan uzak bir şekilde en iyiyi seçebilmeli; ve yönetsel yeteneklere sahip olmalıdır.

Bunu takiben, mekatronik mühendislerinin mühendislik tasarım metodolojisi içinde ne şekilde yer alacakları, katılacakları her bir aşamaya nasıl katkılarda bulunacakları ve bu katkıları en başarılı şekilde ortaya koyabilmeleri için örgüt yapının nasıl şekillendirilmesi gerektiği ortaya konmuştur. Ayrıca bu aşamada mekatronik mühendislerinin neden daha başarılı baş teknolojist olacakları izah edilmiştir. Elde edilen sonuçlar şunlardır:

- **Ürün planlama safhasında üstlenecekleri teknoloji takibi görevini göz ardı edersek, mekatronik mühendisleri esas olarak mühendislik tasarım**

metodolojisinin “problemin netleştirilmesi”, “içeriksel tasarım” ve “yapısal tasarım” aşamalarında yer almalıdırlar.

- Mekatronik tasarım ekibinin örgütsel yapısı en azından matris organizasyon yapısında olmalı ya da en uygunu proje organizasyonu şeklinde olmalıdır.
- Multi-disipliner mekatronik mühendisleri tek disiplinli bir mühendisten daha iyi baş teknolojistlik yapacaklardır.

Çalışmada son olarak, gerçek manada mekatronik ürün ve süreçleri ortaya koyabilmek için mühendislik tasarım metodolojisinin içeriksel tasarım (konsept tasarımı) aşamasında nasıl bir revizyon yapılması gerektiği izah edilmiştir. Buna göre:

- Gerçek bir mekatronik uygulamanın ortaya konabilmesi için tasarımı yapılan sistem bir bütün olarak ele alınmalı ve tasarımcılar son ürün odaklılığını benimseyip (çözüm odaklılık) bunu bütün tasarım aktivitesi boyunca korumalıdırlar.
- İçeriksel tasarım aşamasında öncelikle her bir alt fonksiyonun kategorisi belirlenmelidir. Kategoriler belirlenirken yararlanılacak temel bilgi: veri işleme ve iletişim işlerinin yazılım uygulamalarıyla, kontrol ve koordinasyon işlerinin kontrol uygulamalarıyla ve malzeme taşınması, güç aktarımı, yapı oluşturma ve estetiksel öğelerin mekanik uygulamalarla daha başarılı yapılabileceğidir. Elektriksel uygulamalarsa elektriğin tüketildiği, depolandığı, işlendiği ve/veya üretildiği her yerde olacaktır. Alt fonksiyonlara çözüm aranırken de öncelikli olarak bu kategorilere uygun çözümler bulunmaya çalışılmalıdır.

  Eğer kategorilere ayırma işlemi başarıyla tamamlanırsa hatalı yönelimleri ve genel (adî) çözüm fikirlerini yıkmak, nispeten erken bir aşamada tasarımın genel bir görüntüsünü oluşturmak ve böylece bütünleşik çözümler elde edebilmek ve ayrıca alt fonksiyonlar arasındaki etkileşim ve ekstra kısıtları ortaya çıkarabilmek mümkün olacaktır.
- Mühendislik tasarım metodolojisinin içeriksel tasarım safhası, tasarım ekibini, alt fonksiyonlar arasındaki etkileşim ve ekstra kısıtları ortaya çıkararak bütünleşik bir entegrasyonu ve sinerjiyi elde edebilmelerini mümkün kılacak şekilde yönlendirmelidir.
- Gerçek bir mekatronik uygulamanın tasarımı için tasarım ekibi mümkün olan en erken safhada tasarımın bir genel görünümünü ortaya koyabilmeli ve eğer mümkünse daha işin başında bütünleşik çözümler bulmaya çalışmalıdır.

Sonuç olarak yapılan çalışma, yukarıda ifade edilen bulguların ışığında, ortaya konan yeni içeriksel tasarım metodolojisinin intra-lojistik sürecindeki bir uygulamasıyla sonuçlandırılmıştır.

USE OF MECHATRONICS APPROACH IN PRODUCT AND PROCESS DESIGN

ABSTRACT

Considering its increasing importance and the place that it has already gained in our lives, mechatronic applications are evaluated in this thesis. First of all, the meanings that are appointed to the word mechatronics after Japan's Yasakawa Electric Company has first coined it in 1960s and added to the literature is evaluated together with a number of definitions of it and the historical developments of regarding applications are investigated just before the evaluation of historical evolution of design methodologies. Through these evaluations definition of mechatronics is made as: Mechatronics is the methodology of designing and manufacturing of products and processes which include a complete and synergistic integration of mechanical, electrical, control, and software applications inside and in which all of these tasks are inseparable parts of the solution that the product or the process performs out for its owner.

After then, superiorities of mechatronics are pointed out when compared with electromechanical and single disciplinary applications. Later on, engineering design methodology is evaluated in details and an examination of the most appropriate design methodology that could create actual mechatronics is carried out. For that purpose, fist of all, the importance of entrance of mechatronics engineers to the engineering design methodology and their foreseen contributions are explained. The first proposal that is made and explained at that point is: In order to create actual mechatronics, the design team must be fully structured by or at least must include some "mechatronics engineers". These mechatronics engineers must be multi-disciplined engineers who would know the constraints, priorities, strengths and weaknesses of all related engineering disciplines; who would know at least a little bit of everything of the jargons of these disciplines as well as marketing, sales, finance and other related groups and so create a bound between them by establishing a common interface language; who would get over conflict through negotiations and make the best trade-offs without being impressed by the pride of their background; and who would have managerial skills.

Following that, answers to the questions about how mechatronics engineers could enter the engineering design methodology, what contributions they could make to each phase, and how the organisational structure should be in order to be able to make these contributions successfully are pointed out.

- Mechatronics engineers must be mainly situated in "clarification of the task phase", "conceptual design phase", and "embodiment design phase" of engineering design methodology. Omitting the fact here that they may be the technology pursuit team of the organisation, they are not expected to play any important role either at "product planning phase" or at "detail design phase".

- The structure of mechatronic design team requires at least a matrix organisation and a project organisation would make the best structure. In any case, mechatronics engineers are expected to be the team leaders of each engineering group.
- Mechatronics engineers would become better CTOs than a single disciplinary specialist or generalist.

Finally, a revision in conceptual design phase of engineering design methodology, which is necessary for creation of actual mechatronics, is proposed. Findings are:

- In order to be able to design actual mechatronics, the designed system must be considered as a whole and designers must adopt the end-product focus and keep it alive throughout the whole design activity.
- While developing the concept of the design through the conceptual design phase, the categories of the sub-functions must be defined according to the general information that "data processing and communication activities can be better carried out by software applications; control and coordination activities can be better carried out by control applications; material movement, power transmission, housing and aesthetics can be better provided by mechanical applications; and electrical applications take place in everywhere that electricity is consumed, stored, processed, or produced" and solution ideas must be tried to be found within these categories first if possible.

  If such an activity is successfully carried out then the initial inclinations and common solution ideas can be broken down; an overall view of the whole design can be obtained at an early stage and combined solutions can be found; and evaluation of the possible effects and extra requirements between sub-functions becomes easy.
- Conceptual design phase of engineering design methodology must direct the design team to evaluate all the possible effects and extra requirements between all sub-divisions (regardless of which sub-functions they belong) in order to create a complete integration and synergy.
- For the design of actual mechatronics, design team must create an overall view of the whole design as early as possible in the design activity and find combined solutions at the beginning if possible.

Eventually, under the lights of all above investigations and findings, the thesis is completed with an application of proposed conceptual design methodology to an intra-logistics system.

1. INTRODUCTION

The word, mechatronics, is composed of two different words, namely “mecha” from mechanism and “tronics” from electronics. The author of the word is Japan’s Yaskawa Electric Company. It is firstly used in the late 1960s by the engineers of Yaskawa Electric Co. in order to define the products and processes in which both mechanical and electrical components took place together. They had also made an inference and told that “Technological developments will be incorporating electronics more and more into mechanisms intimately and organically and making it impossible to tell where one ends and the other begins” (Bishop and Ramasubramanian, 2002). As if it was trying to confirm this inference, rapid advances in actuators, sensors, power electronics, integrated circuits, microprocessors, digital signal processors, computer aided design (CAD) techniques, and computational software has opened a gate to a new and attractive way to walk on, and eventually, it came out to be a reality that today’s products began to include quite complicated combinations of different engineering disciplines, namely, mechanical, control, software, and electronics engineering.

Although its acceptance was evolutionary rather than revolutionary (by O. Deobelin; quoted in Ashley, 2003), this primary definition and the word, mechatronics, have been accepted by both industrial and academic areas and have gained fame in the following years. Thus, starting from the creation of its name, a number of different articles evaluating the mechatronics applications have been published. In the meantime, in order to meet the unbounded customer requirements manufacturers had already started to add more and more electronics and software components into traditionally mechanical products. In today’s products, components of different engineering fields are already combined to each other such that the scientific/technical developments of the past few years have shown that innovation occurs mainly at the interfaces of the knowledge fields (Bosch, 2000). That is, it is easy to imagine that in the following years, today’s thoroughly single disciplinary products and processes will be replaced by mechatronics substitutes. For example, in today’s completely mechanical brakes, electromechanical actuators will replace hydraulic cylinders, wires will replace brake fluid lines, and software will mediate between the driver’s foot and the action that slows the car (Iserman, 2003). Furthermore, intelligence will be added into seemingly dumb products, such as radios, televisions, refrigerators, washers, dryers, automobiles, machine tools, medical equipment, toothbrushes etc. (McNamara, 2001). Eventually, many of the products around us will get smarter, offer more features, fill smaller volumes, and carry out better performance.

Depending on above explanations, it is thoroughly evident that on the side of product, technology is going on the way to create an environment/a market which will be surrounded by completely mechatronic products. However, as I will try to explain in ‘Definition of Mechatronics’ chapter, the meaning and so the definition of mechatronics is much more than its combined words imply. In that chapter, I evaluate the definitions of a number of academicians and industrial people. At the end I make a much broader definition for mechatronics.

A detailed examination of ‘Elements of Mechatronics’ is carried out just before evaluation of the ‘Date by Date History of Mechatronics’. Thorough the ‘Elements of Mechatronics’ chapter, basic components of mechatronics are evaluated. Purpose and place of use of each of these sub-sciences are pointed out and pros and cons of each of them are explained. Later on, historical development of mechatronics is explained by the technological developments of its elements in the ‘Date by Date History of Mechatronics’ chapter.

In order to better evaluate advances that could have affected the creation and development of mechatronics, I evaluated the historical changes in design methodologies. For that purpose, starting from craft engineering methodology I evaluated sequential engineering methodology and concurrent engineering methodology in ‘Change of Design Methodology’ chapter. In this chapter, basic ideas of each design method are examined; pros and cons of each of them are shortly explained; and a historical development of design methodologies are tried to be presented. It is easy to see in this chapter that together with the technological changes in products, the methods, which are creating these products, are also changing. With another perspective, we may say that designing method of a product or process may reasonably affect the type of it whether it is single disciplinary, electromechanical, or mechatronics.

Superiority of mechatronics when compared with conventional (electro-mechanical or single disciplinary) ones are explained in 'Superiority of Mechatronics' chapter. I have tried to give examples and explain foreseen advantages of mechatronics one by one in that chapter.

Starting with the idea that designing method of a product or process may reasonably affect the type of it, firstly, I evaluated the engineering design methodology thorough the 'Engineering Design' chapter in order to have basic information for design. I mainly adopt to the engineering design methodology of Pahl and Beitz although I have evaluated a few different design approaches. The basic steps are the same in all of these methodologies but the methodology of Pahl and Beitz is more systematic. Therefore, in 'Engineering Design' chapter I mainly applied to the methodology of Pahl and Beitz.

After making all that literature search and examinations of all the gathered information, I make my main contribution throughout the 'Proposed Design Methodology' chapter. I make my first proposal for the use of mechatronics engineers in engineering design methodology in chapter 'Superiority of the Use of Mechatronics Engineers in Design'. Determining the lacking points of conceptual design in creation of actual mechatronics, I firstly propose that entrance of mechatronics engineers into engineering design methodology may fill out these lacking points and makes it easy to exceed the synergy and complete integration barrier. In the meantime, I make my definition for mechatronics engineers. That is, I point out expected characteristics of a mechatronics engineer. At the second half of the chapter, I support my idea by finding out an inclination in historical development of design approaches such that all the engineering disciplines and so their knowledge is inclining to merge and create a complete integration in one multi-disciplined engineering field.

Later on, after making it clear that mechatronics engineers are essential for the design of actual mechatronics, I try to find out, in chapter 'New Structuring of Product Development Department', at which steps of engineering design methodology mechatronics engineers are needed and what kind of contributions they may probably make. Considering their formerly appointed abilities, I determine the expected contributions of mechatronics engineers for each step of engineering design methodology in the first sub-title of ‘New Structuring of Product Development Department’ chapter, namely ‘Place of Mechatronics Engineers in the Engineering Design Methodology’ chapter. After then, I build up an organisational structure for the design team. At this structure, I underline the managerial abilities of mechatronics engineers and appoint another characteristic for mechatronics engineers. In this chapter again, I evaluate the most suitable organisational structure for the whole organisation as well. Examining the possible organisational structures, I determine the essential structure for mechatronics design methodology.

At the second sub-title of, ‘New Structuring of Product Development Department’ chapter, namely ‘What Makes Mechatronics Engineers a Good Chief Technology Officer’, I make a new proposal that beside their contribution to design methodology mechatronics engineers can make another contribution to the technology pursuit of organisations. For that purpose, I initially evaluate the common responsibilities of chief technology officers and determine the needed abilities for better carrying out these responsibilities. The determined abilities for chief technology officers at this chapter, surprisingly, completely meet the formerly determined characteristics of mechatronics engineers. Therefore, I propose that mechatronics engineers may become better CTOs compared with single disciplinary specialists or generalists.

Eventually, in chapter ‘Conceptual Design of Mechatronic Products and Processes’, I examine the competence of the engineering design methodology of Pahl and Beitz for the creation of actual mechatronics and propose an enlarged conceptual design phase for mechatronics design methodology. Firstly, I determine the obligatory factors for the creation of actual mechatronics and make a number of related proposals. Later on, under the lights of primarily determined factors, I propose a new structure for conceptual design of engineering design methodology by enlarging the methodology of Pahl and Beitz in order to meet the obligatory factors of mechatronics design activity.

The application of that proposed conceptual design, namely combined engineering design or mechatronics design methodology, is made with a case study. In chapter ‘Case Study: Conceptual Design of an Intra-Logistic System’, I have applied my proposed design approach to an actual system design activity which is carried out in Arcelik A.S. Washing Machine Plant. Starting with a primarily defined design problem, I applied my approach to the design of a process step by step and finished the concept design with a detailed concept assembly, namely with a principle solution.

Consequently, I sum up all my findings in chapter ‘Findings’ and conclude my thesis with the final ‘conclusion’.

2. DEFINITION OF MECHATRONICS

The original definition of mechatronics was first made by the Yasakawa Electric Company in late 1960s. The word is composed of two pieces such that “mecha” from mechanism and “tronics” from electronics. As its name implied, the generators of the word wanted to announce that the current and foreseen developments in technology has been incorporating electronics more and more into mechanisms and it would probably be impossible to tell where one ends and the other begins (Bishop and Ramasubramanian, 2002). Although its acceptance was evolutionary rather than revolutionary (by O. Deobelin; quoted in Ashley, 2003), this primary definition and the word, mechatronics, have been accepted by both industrial and academic areas and have gained fame in the following years. Therefore, there have been made many different definitions of mechatronics from different perspectives with different words. In all of the definitions, the multidisciplinary structure of mechatronics is mentioned; however, in many of them another characteristic is added to the meaning of the word. For example, having a mechanical engineering perspective Masayoshi Tomizuka, professor of mechanical engineering at the University of California, Berkeley, says that “The basic idea in mechatronics is to apply new controls to extract new levels of performance from a mechanical device” (quoted in Ashley, 2003). It is easy to see the pressure of his background in mechanical engineering on Tomizuka that he puts the mechanical components onto the focal point of a mechatronic product and considers electronic components as auxiliary parts. On the other hand, having in mind the precedence of mechanical structures, an electrical engineer, Amerongen, emphasizes on the importance of electronic components. He says that “Although a proper controller enables building a cheaper construction, a badly designed mechanical system will never be able to give a good performance by adding a sophisticated controller”. Then, he makes his definition as “Mechatronic design is the integrated design of a mechanical system and its embedded control system” (Amerongen, 2003). Both of the definitions sort every product which includes both mechanical and electrical components in the category of mechatronics. However, should we categorize every multidisciplinary product in mechatronics?

The answer to above question is “yes” from the perspective of some specialists as mentioned above. However, there are many other points of view which are claiming and insisting on the idea that mechatronics is something more than just a simple combination of mechanisms and electronics. For instance, W. Bolton says that “A mechatronic system is not just a marriage of electrical and mechanical systems and is more than just a control system; it is a complete integration of all of them” (quoted in Bishop and Ramasubramanian, 2002). The idea given here walks one step further and enlarges the meaning of the word, mechatronics, from a simple combination to a complete integration of different disciplines. By the word, complete integration, Bolton wants to say that a mainly mechanical system with a control system which is simply added afterwards in order to increase functionality is not an actual mechatronic system but the control system must be an inseparable part of the main system while performing its work. Another definition goes further such that it says: “Mechatronics originates from electromechanical systems wherein electronics are integrated into mechanical systems. However, mechatronics is more than just a simple integration but rather it is a synergistic integration” (ATIP Reports, 1998). The word added into the meaning of mechatronics by this definition is “synergy”. The synergistic aspect here means that each of the different subtasks of the machinery should be realized in the most efficient way (Shöner, 2003). The synergistic approach in the meaning of mechatronics has gained wide acceptance. As many others Ashley supports the same idea and says: “The word’s (mechatronics’) meaning is somewhat broader than the traditional term electromechanics” and adds “Mechatronics denotes a synergistic blend of mechanics and electronics” (Ashley, 2003).

All of the definitions above are concerned with the product and to a degree its designing approach. Mechatronics is even broader, however. To name, Harashima, Tomizuka, and Fukada enlarges the meaning of the word with their definition by saying “Mechatronics is the synergistic integration of mechanical engineering, with electronics and intelligent computer control in design and manufacturing of industrial products and processes” (quoted in Bishop and Ramasubramanian, 2002). The definition underlines that mechatronics is not only related with the product but also with the processes which produces the products. Another thing to point out is that mechatronics takes into account the manufacturing of products while considering their design. Somewhat a similar definition comes from European Economics Community such as “Mechatronics is the synergistic combination of precision mechanical engineering, electronic control and system thinking in the design of products and manufacturing processes” (quoted in Tomkinson and Horne, 1995). Same as the preceding definition, importance of manufacturing processes in mechatronics is emphasized.

Like these ones above, different definitions carried the meaning of the word, mechatronics, to different edges and end-points. For example, being multidisciplinary is spoilt in one definition: Mechatronics describes the Japanese practice of using fully integrated teams of product designers, manufacturing, purchasing and marketing personnel acting with each other to design both the product and the manufacturing system (Hunt, 1988). Some others specify how to share functionality such as “Mechatronics is the multidisciplinary combination of *brains* of electronics, control, and software with the *muscles* of mechanical systems” (Hollingum, 1999). A similar point of view comes from D.M. Auslender, professor of mechanical engineering at Berkeley, “any system in which you control or modulate power is a candidate for computer control. For any mechanical component you can ask the question: What is its purpose? Does it transmit power? Or is its purpose control and coordination? Computers, software and electronics can generally do this second function more efficiently, simpler, cheaper, with much more flexibility” (quoted in Ashley, 2003). Another definition is technical, more explicit, and referring to the leading edges describes the word by its elements: “Mechatronics is the integrated design, analysis, optimization, virtual prototyping, and fabrication of intelligent, high performance electromechanical systems featuring, system learning, adaptation, decision making and control through the use of advanced hardware (e.g. actuators, sensors, microprocessors, digital signal processors, power electronics, integrated circuits) and leading-edge software (Giurgiutiu, 2004).On the other hand some definitions are more implicit, simple, and on the information side such as: “Mechatronics is the integration of electrical and mechanical engineering knowledge from design to manufacturing (Thomkinson, 1992). Finally, on another edge-point is a different definition which creates a fantastic perspective by adding art and history in its definition. The definition depends on the information that the term “Mechanics” had been used in old Greece for the art of designing helpful machinery, and in this sense it says: “Mechatronics can be seen as the modern way to design *helpful machinery* including electronic technologies (Schöner, 2003).

Beside the quarrel about what the word mechatronics actually means is another issue which mainly goes on the academic side and is about whether mechatronics is a new science slowly growing up or just a methodology demonstrating a new way of doing things. Academicians are straightforward on this issue and they say that mechatronics is a methodology used for the optimal design of mechatronic products. Then, there comes a description of what a methodology is: A methodology is a collection of practices, procedures, and rules used by those who work in a particular branch of knowledge, or discipline (Shetty and Kolk, 1997). Similar to this description John Milbank, of the University of Salford, U.K., supports

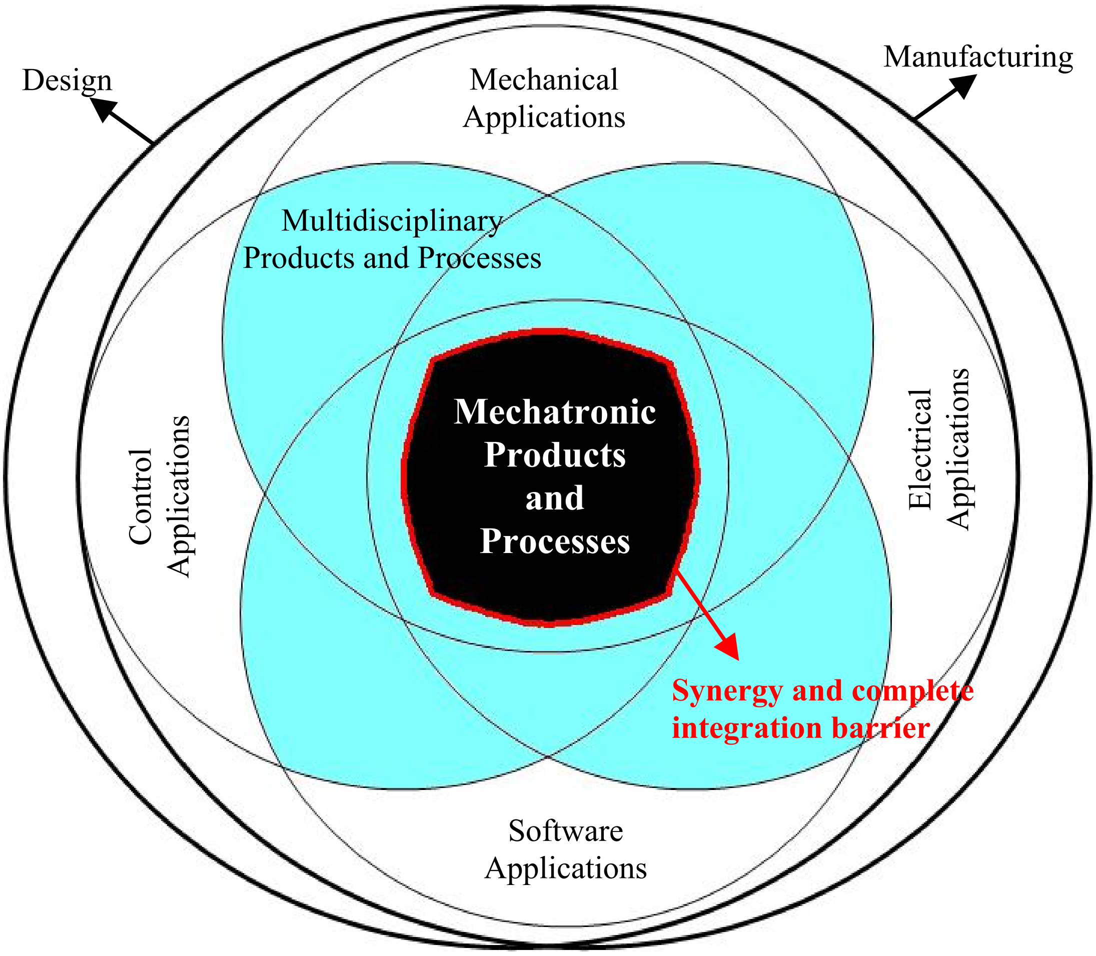


Figure 2.1: Mechatronic Systems

the same idea by saying: "Mechatronics is not a subject, science, or technology perse- it is instead to be regarded as a philosophy- a fundamental way of looking at and doing things, and by its very nature requires a unified approach to its delivery" (Thomkinson and Horne, 1995). Another support comes from the industry that Takashi Yamaguchi, who works at Hitachi Ltd.'s Mechanical Engineering Laboratory in Ibaraki, Japan, says that mechatronics is a methodology for designing products that exhibit fast, precise performance.

The quarrel among scientists, academicians, engineers, and even industrial people about what the word, mechatronics, actually means and whether it is a science, technology, or philosophy continues passionately. However, as the time goes on and the knowledge about the subject increases, the definition or let's say characteristics of mechatronics begins to be clear and straightforward. First of all, it is multidisciplinary. It combines mechanical, electrical, control and computer sciences inside and even brings them together with purchasing marketing, sales, and finance personnel. While being multidisciplinary, it is not a simple combination or integration of different disciplines but rather a complete and synergistic integration of all of them. This multidisciplinary, synergistic integration is not only a designing approach but it also includes manufacturing. In the same sense, it does not only consider the product but also takes into account the processes through which these products are produced. Finally, it is being accepted that it is a methodology/philosophy. That is, it is a new way of looking at and doing things in the engineering fields.

Ultimately, under the lights of investigation and extracts stated above, I make the definition of mechatronics as: "Mechatronics is the methodology of designing and manufacturing of products and processes which include a complete and synergistic integration of mechanical, electrical, control, and software applications inside and in which all of these tasks are inseparable parts of the solution that the product or the process performs out for its owner." (See Figure 2.1).

3. ELEMENTS OF MECHATRONICS

Many products around us have a combination of electrical, mechanical, and software components. Some of them such as television and radar systems consist of a great percentage of electrical components, while some others are mainly composed of mechanical components such as machinery. Still some others such as computers contain significant software content as well as electronic content (Thomkinson and Horne, 1995). However, in some cases it is difficult to say and find out the precedence or dominance of one discipline over the others. For example, CNC machines mostly have a great mechanical content but it is useless without its control system, software applications or complete electrical system. In such cases, in order to be able to make optimal trade-offs between different disciplines to create an optimal product, a synergistic process is needed. Being created through such a synergistic process, mechatronic systems consist of mechanical, electrical, control, and software elements. Each of these elements may take a different form in every product; however, they are assigned and supposed to carry out some specific tasks which are explained in the following subtitles.

Through the history of mechatronic systems, first of all, actuators are added into mechanical systems as the first step of automation. The purpose was to introduce external power into the system and increase actuation forces or actuation speed. In the next step, some sort of control is added and it is followed by some electronics and software applications. By the step, gathering, processing and/or storing of information took its place in the system. Just beside, by the help and push of the technology a big variety of sensors started to take place in the system and as the systems became large or distributed communication networks began to find a space for themselves. Even now and in the future, adaptive and learning systems will be realized too. However, all of these components do not create a mechatronic system -as explained in early chapters- these are the elements that take place in a mechatronic system in different forms. What is more in mechatronics is the synergy and complete integration of them (Schöner, 2003).

Ultimately, we can roughly say that mechatronic systems are mainly composed of (Bosch, 2000) (See Figure 3.1):

- a basic mechanical structure which has to be capable of housing all the physical matters and carrying out some certain movements, actions;
- sensors which act as data collectors on the system or from the environment;
- processors which are the brains, decision makers, or regulators of the system by evaluating the data, creating information, and activating the corrective actions;
- actuators which are the power suppliers or generators of the system by creating forces, movements, or supplying voltages or other quantities which act on the basic system or its environment according to the activation of processors.

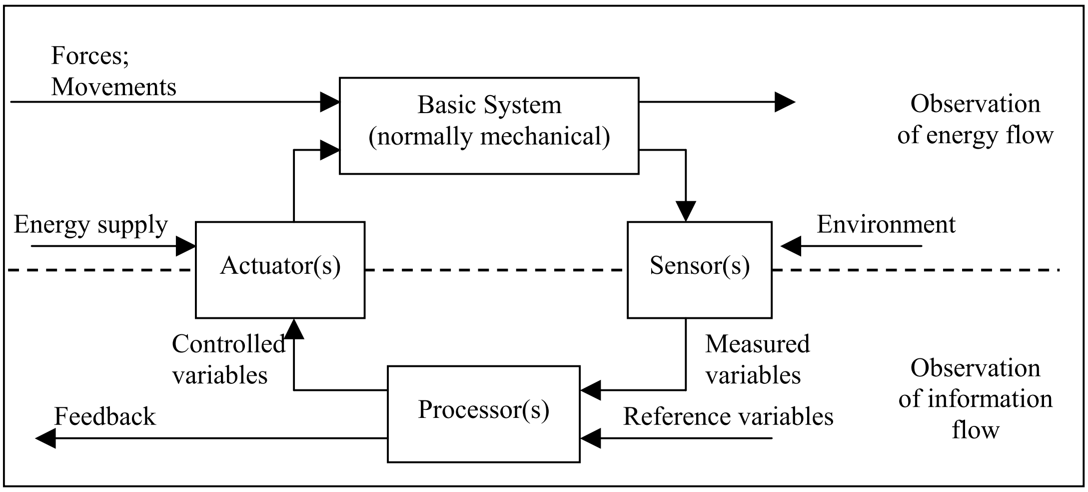


Figure 3.1: Basic structure of mechatronic systems (Bosch, 2000, pg.13)

3.1 Mechanical Components

A mechanical component can be defined as a component which has physical characteristics such as length, width, height, and mass. Mechanical components provide the structure to house functionality, provide rigidity, enable physical stability, and provide aesthetics. It gives the product substance and determines fit constraints and form. Additionally, Mechanical components can be combined into an assembly and provide functionality such as that provided in a piston, crankshaft, and cylinder walls (Thomkinson and Horne, 1995). Although mechatronic solutions are much smarter, mechanisms might still be used to provide some functions as: force amplification that given by levers, change of speed that given by gears, action at a distance that given by hydraulics or belts, etc. (Bolton, 1995).

Mechanical systems are concerned with the behaviour of matter under the action of forces. Such systems are categorized as rigid, deformable, or fluid in nature. Newtonian mechanics provides the basis for most mechanical systems and consists of three independent and absolute concepts: space, time, and mass. A forth concept, force, is also present but is not independent of the other three (Shetty and Kolk, 1997).

Some of the concerns regarding a mechanical component or assembly include whether the structure, substance, or each of the components is rigid enough to withstand the working environment of the product. How do all the components and assemblies fit together? More specifically, what is the relationship with the electrical, control, or software components? And finally, what about manufacturability and serviceability? Some other concerns are (Thomkinson and Horne, 1995):

- Is there enough space between electrical components to ensure there is not electrical interference? Is the package large enough to accommodate properly located electrical components?
- What materials and configuration are needed to address rigidity and provide shock resistance for electrical components and assemblies?
- What kind of a cooling method should be used and where they should be located?
- How can the weight be minimized?
- Can the package be manufactured as defined?
- Can the assemblies and components housed by the package be easily assembled and disassembled?

3.2 Electrical Components

An electrical component can be defined as a component that consumes, stores, processes, or produces electricity. These components provide the intelligence for the product (Thomkinson and Horne, 1995). Electrical systems are concerned with the behaviour of three basic quantities: current, voltage, and resistance (Bosch, 2000). These systems consist of two categories: power systems and communication systems. Communication systems are designed to transmit information as low-energy electrical signals between points. Such functions as information storage, processing, and transmission are common parts of a communication system. This area of electrical engineering is often called electronics. Power systems on the other hand are designed to transmit large quantities of electrical energy, not information, between points efficiently. Frequently, rotating machines are used to convert the energy between electrical and mechanical domains. Generators convert energy from mechanical to electrical and motors are used to convert it back (Shetty and Kolk, 1997).

Basic elements of an electrical system are current, resistance, inductance, capacitance, insulators, semiconductors, power generators, switchgears, cables, and relays (Bosch, 2000). In mechatronic products we mainly see them in the form of motors, generators, sensors, transducers, circuits, amplifiers and contact devices (Shetty and Kolk, 1997).

The impact of the use of electrical components can be significant in a couple of ways. First, adding electronic capability to a mechanical system often simplifies the resulting mechanical system by reducing the number of components and moving parts. This simplification is accomplished by transmitting complex functionality such as accurate positioning from the mechanical system to electronics. Second, adding electronics enables functionality that otherwise would have been unachievable. An example of this is antilock brakes for automobiles, a speed sensor which in turn adjust the pulse of brake force while braking on slippery surfaces (Thomkinson and Horne, 1995).

3.3 Software Components and Control Components

Software is defined as the routines and logical instructions to be interpreted by the electrical components. The electrical components and assemblies combined with software capabilities provide the bulk of functionality of *intelligence* in today's products. They are inextricably tied together (Thomkinson and Horne, 1995).

Computers originated after it was found that certain electronic circuits displayed behaviour similar to some of the basic brain functions and when connected together could think in a primitive way. Computer science is the study of how such circuits should be connected together to think efficiently. The process includes software as well as hardware. For mechanical applications, computer system hardware is usually restricted to computer-specific circuits and devices. These include logic networks, flip flops, counters, timers, triggers, integrated circuits, and microprocessors. Fast computer hardware is of little value without the appropriate software to operate it (Shetty and Kolk, 1997).

Ultimately, all communication with a computer is in terms of ones and zeros. Computers can be programmed at several levels. Chip level programming is called machine language. Assembly language was first step toward a higher level language. In the late 1970s visual programming languages began appearing. After integrated systems are introduced, their block-diagram based Matrix programming environment in the early 1980s, visual languages really took off.

Computer systems are basically and naturally the brains/decision making units of mechatronic systems. Again as naturally as how a brain needs some inputs provided by eyes, ears, nose, tongue, and skin and some kind of power support provided by muscles and other vital organs of the body; computer systems need some inputs provided by sensors and power support provided by actuators, electrical systems, and mechanical systems.

Actuators and sensors are the basic elements of a control system. Sensors are required to monitor the performance of machines and processes. Mechatronic systems use sensors to convert mechanical measures into electrical signals. Computer algorithms issue commands to actuators based on sensor outputs. The actuators convert electrical inputs to mechanical motions (Karnopp and Margolis, 2001).

Using a collection of sensors, one can monitor one or more variables in a process. Sensing systems can also be used to evaluate operations assess machine health, inspect the working progress, and identify parts and tools. Sensors are needed to provide real time information that can assist controllers in identifying potential bottlenecks, breakdowns, and other problems with individual machines and with a total manufacturing environment before they upset production. Some of more commonly measured variables in mechatronic systems are: temperature, speed, position, force, torque, and acceleration. The characteristics tat are important when one is measuring these variables include the dynamics of sensors, stability, resolution, precision, robustness, size, and signal processing (Shetty and Kolk, 1997).

The other important component of mechatronic systems are actuators. Actuation involves a physical acting on the process such as the ejection of a work piece from a conveyor system initiated by a sensor. Actuators are usually electrical, mechanical, fluid power or pneumatic based. They transform electrical inputs into mechanical outputs such as force, angle, and/or position. Actuators can be classified into three general groups (Shetty and Kolk, 1997):

- Electromagnetic actuators (e.g., AC and DC electrical motors, stepper motors, electromagnets);
- Fluid power actuators (e.g. hydraulics, pneumatics);
- Unconventional actuators (e.g. piezoelectric);

Each of actuation types has pros and cons. None of them is perfect and suitable for every application but superiority or let's say priority of one of them depends on the conditions that the product, process, and their environment face. On the advantage side, for example, electrical systems are highly efficient, has good positioning accuracy and low friction, are easy to control, and largely maintenance-free devices. Additionally, electricity is a very clean type of energy (except generation), provides relatively high safety if all regulations are observed, plant fusing is compliant, and uses lower cost energy carriers than hydraulics and pneumatics. However, on the other side are disadvantages such that electricity is very difficult to store and there happens very high losses when transmitted over large distances. Also, these systems are very open to fire hazards because of sparks; extra cooling is needed and facilities for speed control and regulation are expensive in these systems. Beside the pros and cons of electrical systems, hydraulic systems are easy to control, monitor and check; needs low maintenance and has long life; provides transmission of great forces and powers etc. However, leakage problems happen, danger of loosening connections is obvious, the viscosity of the oil is open to change and it is sensitive to change etc. Similar to electrical and hydraulic actuators, pneumatic actuators and systems have advantages and disadvantages as well. For example, unlimited quantities of air are available anywhere, it can be stored, high piston speeds and short operating times can be achieved etc. However, it is not possible to achieve continuous, constant piston speeds using compressed air; noise levels are high etc. These advantages and disadvantages of each actuation system can be increased (for further information see Bosch, 2000).

4. DATE BY DATE HISTORY OF MECHATRONICS

The development, acceptance and popularity of mechatronics have been through an evolutionary period rather than revolutionary. Although, its name was first coined in the late 1960s, its roots go far back to the depths of history. For one aspect, its history start with the primary automation applications in old Greece from 3rd to 1st century B.C. and for another aspect it has been growing out of robotics and its history was not too long. Actually, the popularity of the word “automation” has evolved after 1940s when it was coined by the Ford Motor Company. The word was first used to denote a process in which a machine transferred a subassembly item from one station to another and then positioned the item precisely for additional assembly operations. However, the use of successful automation applications had been long before its name coined. For instance, the earliest automatic control applications first appeared in Greece from 300 to 1 B.C. with the invention of float regulator mechanisms. The examples are the water clock of Ktesibios and an oil lamp devised by Philon (quoted in Bishop and Ramasubramanian, 2002).

The invention of many important automation applications has occurred just before the Industrial Revolution from sixteenth to nineteenth centuries. One of the first feedback systems, a temperature regulator, was invented by Cornelis Drebbel at the beginning of 17th century. At the same knowledge area a pressure safety regulator for steam boilers was invented by Denis Papin at the end of the century. Other examples are the first mechanical calculating machine of Pascal (1642) and the first historical feedback system of Polzunow (1765) (quoted in Bishop and Ramasubramanian, 2002). Such inventions continued in 19th and 20th centuries and eventually automation was popular after Ford first used it in 1940s. However, until the mid-twentieth century, most control applications was entirely motion based (mechanical), motion-temperature based (thermo-mechanical), or motion-flow based (fluid-mechanical). It was not until the invention of the electronic feedback amplifier by H.S. Black in 1927 that it became possible to combine motion with electronics and producing electromechanical systems. During the period between 1927 and 1975, the use of electronics to modify the behaviour of mechanical systems grew rapidly, especially after the introduction of transistors and microprocessors. Designing of these electromechanical systems has not been based on a formal procedure but an experience based method was in use: Design and built the mechanical system, then paint it and install the controls (Shetty and Kolk, 1997). Within this period in the late 1960s, the name, mechatronics was appointed to denote such kind of products and processes by en engineer at Japan's Yaskawa Electric Co.. After than its name first coined, the word has remained popular in Japan and has been in general use in Europe in the following years. Later on, through an evolutionary period, it's been accepted and gained popularity in all over the world.

In the 1970s, mechatronics was concerned mostly with servo technology which is used in products such as automatic door openers, vending machines and auto-focus cameras. In 1980s, as information technology was introduced, engineers began to embed microprocessors into mechanical systems to improve their performance. Numerically controlled machines and robots became more compact, while automotive applications such as electronic engine controls and antilock-braking systems became widespread. By the 1990s, communication technologies have been added to the mix yielding products that could be connected to large networks. This development made functions such as remote operation of robotic manipulator arms possible. In these days; new, smaller -even micro scale- sensor and actuator technologies are being used increasingly in new products. Micro electromechanical systems such as tiny silicon accelerometers which trigger automotive airbags are examples of latter use (Ashley, 1997).

It depends on our point of view. If we support the aspect which assumes that a science starts from the beginning of each of its sub-sciences then the history of mechatronics starts from 3rd century B.C. with the primary automation applications in old Greece. However, if we support the aspect which assumes that a science starts from the time when its first, simplistic but complete example has occurred then the history of mechatronics starts from late 1920s with the use of electronics in motion controls.

Regardless of the time from which its history starts, the development of mechatronics is on-going and not completed yet. It is not even clear to what end points it may reach. Future developments in electronics, control and software technologies will set a route to the journey of mechatronics in the history.

5. CHANGE OF DESIGN METHODOLOGY

The difference between a mechatronic system and a multidisciplinary system is not the constituents but rather the order in which they are designed (Shetty and Kolk, 1997). Starting from that point of view we may come up to a conclusion that the design methodology of a product or a system may initially determine the type of it whether it is mechatronic, multidisciplinary or fully single disciplinary. If we look through the history of design methodologies we may easily acknowledge this point of view. In the early stages of design methodology almost all the products which has been produced by craft production methods were single disciplinary because they used to be designed and produced by a limited number of specialists who were the specialists of the same area. In the following years, historically together with mass production approaches, there have been used a new methodology which is called sequential design-by-discipline approach and as a result multidisciplinary products were in the field. In this case, for example, the design of an electromechanical system is often accomplished through a three-step-design activity whose steps are carried out in their sequence. First of all the mechanical system is designed. This is followed by the design of power and microelectronics and finally the control algorithm is designed and implemented. Later on, a new methodology took the place of sequential engineering approach. Nowadays, a new design methodology which is called concurrent engineering or simultaneous engineering methodology is popular. Engineers of different fields start their design activity at the same time in this case. They usually come together, try to work together and carry out the design activities all at once.

The mechatronic design methodology on the other hand requires a concurrent approach at the smallest degree instead of sequential approach and as I am going to point out in the following chapters, the ideal mechatronic design can only be the result of "*combined engineering methodology*". Under the following tittles, I am going to summarize the historical development of design methodology and demonstrate pros and cons of each of the approaches.

5.1 Craft Engineering Methodology

Craft engineering methodology is the main design method which has been in practice in the early times of industrial revolution. It’s actually not reasonable to call it a methodology but it was a simplistic practice of designing. In the craft production age, almost all the components and each separate part of a complicated product is designed and produced by different producers in small workshops. In craft production, the customers would directly contact to an entrepreneur, who would organize all the production and assembly activities, and explain them what kind of a product they wish. This entrepreneur contacts to each of the component producers and makes his orders for very special and single parts. Then, each of the component producers designs and produces the desired part without considering the role of that component in the main product. They would not necessarily be in contact with the producers of related parts either. After receiving all the components, the entrepreneur organizes the assembly activities. The assembly of the main product begins with the assembly of first part to the second after a difficult levelling activity which was necessary in order to adjust these separately designed parts to properly assemble to each other. Then the third part is assembled to the first two after levelling again. This assembling by levelling activity would continue till the end of whole assembly of the main product and it would be carried out by a very talented and experienced workforce.

Basic characteristics of craft engineering methodology can be summarized as following (Womack and others; 1990):

- Responsibility of designing and production of separate parts is so much distributed. There is not any relation or synergy between these distributed producers. The assembly of main product and production of each separate part is organized by an entrepreneur who would not have much effect on these separated producers (workshop owners) during designing and production.
- End products and each of its parts are mostly single-disciplinary. Mechanical components are thoroughly domestic.

5.2 Sequential Engineering Methodology

“Design and built the mechanical system. Then bring in the painters to paint it and the control system engineers to install the controls.” (Shetty and Kolk, 1997). A simple but essential definition of sequential engineering design methodology is hidden in these sentences. As its name implies, different engineering disciplines carries out their works in their sequence in this approach. Under precedence of mechanical design, electrical, control, and software engineers adds some functions and characteristics to the main product in their order.

Through the end of industrial revolution, many technological developments in control and electrical engineering fields have occurred. Parallel to these developments, products started to be multidisciplinary. Some electrical and control applications are added to dully mechanical products to enhance their abilities. Both mechanical and electronic engineers were employed in big manufacturers each with their own well-defined capabilities. These engineers worked together but rarely got involved with each other’s activities. The product travelled between different engineering departments and each department added the related characteristics on the body.

The emphasis is again on mechanical design. The basic structure is designed by mechanical engineers, so does the basic performance of the product is still carried out by mechanical elements. Later on, the semi-structure passes to the hands of electrical and control engineers. They add some auxiliary functions to increase its attractiveness and control functions to increase its performance. Control algorithm and some software applications are added after all.

This sequential engineering approach usually results in suboptimal designs (Ashley, 2003). Control and electronic engineers can not add much to the functionality. Even it is very difficult to add proper controls because fixing the design at various points in the sequence causes new constraints, which obviously rather complicates the performance of next discipline (Shetty and Kolk, 1997). Furthermore, control system engineers need a throughout understanding of the mechanical parts in order to correctly model the control algorithm (James, 2004). However, in many cases it is very difficult to a pure electrical engineer to understand the constraints of mechanical engineers and vice versa.

5.3 Concurrent Engineering Methodology

Concurrent engineering is a design approach in which the design of a product and manufacturing of a product are merged in a special way. Traditional barriers between design and manufacturing are removed. During the design stage, even customer perception, market analysis, life cycle performance, quality, reliability, and sales are also taken into account. Product design and process planning take place concurrently. The total philosophy of concurrent engineering in the organization is well suited for team-oriented project management, with emphasis on collective decision making (Shetty and Kolk, 1997).

There are two common themes in concurrent engineering. The first is that the initial design work must account the needs of all affected downstream processes. This theme further focuses on the timeliness of these considerations. Team members from different disciplines of engineering come together. Considering the ideas, needs, and boundaries of each party, they try to find proper solutions to the design problems. Every different engineering group start their design works at the same time. Even after creation of initial solution ideas manufacturing activities start simultaneously as well. The other important theme of concurrent engineering on the other hand is *better team work*. How better the sharing of ideas, understanding of boundaries and strengths of each other, determination of trade offs, and understanding of each other in negotiations are; how better the team work is. How better the team work is, how effective the concurrent engineering methodology is (Tomkinson and Horne, 1995). Successful implementation of concurrent engineering is possible by coordinating adequate change of information and dealing with organizational barriers to cross-functional cooperation. Due to the influence of concurrent engineering, traditional barriers between different disciplines of engineering have decreased; however the lack of common interface language makes the information exchange in concurrent engineering difficult (Shetty and Kolk, 1997).

In concurrent engineering, a development team is formed of members of different engineering fields. They keep relation with their own field/department but they are strictly tied to the development team leader. The main product does not travel between departments as sequential engineering approach. Thus, all of the different engineering applications start at the same time and at the same place. All team members are involved in every steps of design and they have the rights to declare their own ideas for each other’s applications. Therefore, communication between different disciplines is at the top level. Also, design period is much shortened.

Implementations of concurrent engineering usually take one of two forms (Tomkinson and Horne, 1995):

1. The first approach is to spin off a smaller organisation outside the mainstream of standard corporate bureaucracy and force it to implement concurrent engineering. This concept was used very successfully by Chrysler Motors for the design of the Viper Car.
2. The second approach is to implement concurrent engineering within the standard corporate structure. One common way to do this is to start integrating the activities of two departments, add a third department and so forth until all departments are working cooperatively using the concurrent engineering model.

6. SUPERIORITY OF MECHATRONICS

Mechatronics may sound like a utopia to many product and manufacturing managers because it is often presented as the solution to nearly all of the problems in manufacturing (Chapman and Hall, 1988). As it is going to be discussed in this chapter mechatronics promises to provide many superiorities over the conventional systems. Particularly, a dramatic increase in productivity is promised. With the extensive use of mechatronic elements such as computer aided design (CAD) and computer aided programming (CAP), design changes as so easy. Flexible manufacturing systems (FMS), computer aided design and computer-integrated manufacturing (CIM) equipments cut the turnover time for manufacturing. These systems minimize production costs and greatly increase equipment utilization. Connections of CAE, CAD and CAM help creating designs that are economical to manufacture; control and communications are improved with minimum paper flow; and CAM equipment minimizes time loss due to set up and material handling.

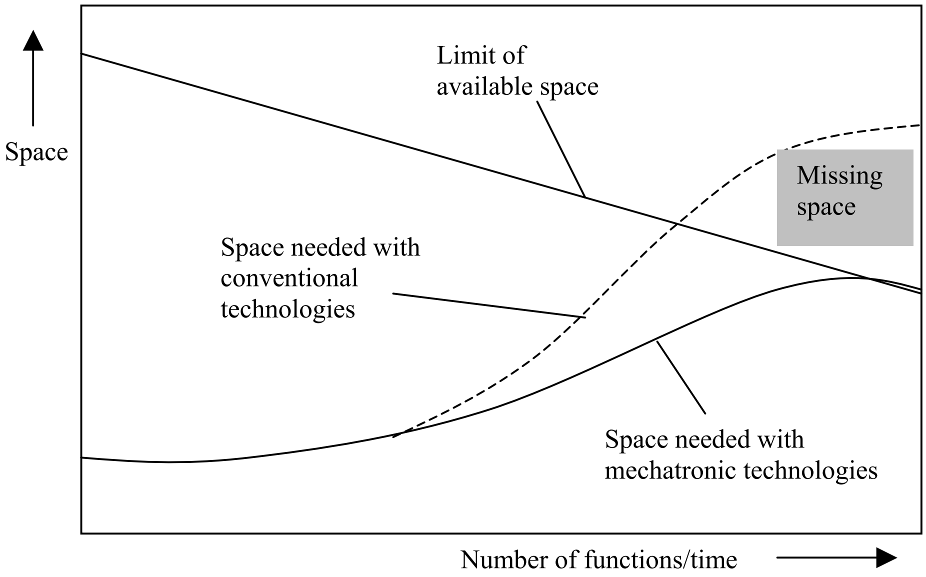


Figure 6.1: Limited Space for Vehicle Functions (Runge, 2001) (quoted in Schöner,2003)

The increasing number of functions over time would need more and more space using conventional technologies, which is in contrast to the decreasing amount of space at disposal for the implementation of these functions (see Figure5.1 as an example). Only using mechatronic integration as a means for compact realization, such systems can be fit into today's technological products. In addition to space, cost is the other essential boundary condition for functional improvements in products. Typical cost shares of an electronically controlled actuator before the efforts of mechatronic integration, the electronics stand for 50% of the total cost. Within this share, 50% of the cost of electronics is related to mainly mechanical parts, like cooling, housing, circuit board, connectors and cables. One goal of mechatronics is to reduce some of the cost related to the mechanical parts of the electronics by combining it suitably with other parts of the mechanical construction (Schöner, 2003).

The primary benefits of mechatronics, with an emphasis on advanced manufacturing technologies and factory automation, are summarized below.

- *High Capital Equipment Utilization:* Typically, the throughput for a set of machines in a mechatronics system will be up to three times that for the same machines in a stand-alone job shop environment. The mechatronic system achieves high efficiency by having the computer schedule every part to a machine as soon as it is free, simultaneously moving the part on the automated material handling system and downloading the appropriate computer program to the machine. In addition, the part arrives at a machine already fixtured on a pallet (this is done at a separate work station) so that the machine does not have to wait while the part is set up (Hunt, 1988).
- *Reduced Capital Equipment Costs:* The high utilization of equipment results in the need for fewer machines in the mechatronic system to do the same work load as in a conventional system. Reductions of 3:1 are common when replacing machining centres in a job-shop situation with a mechatronic system (Hunt, 1988).
- *Reduced Direct Labour Cost:* Since each machine is completely under computer control in mechatronic systems, full-time oversight is not required. Direct labour can be reduced to the less skilled personnel who fixture and defixture the parts at

the work station and a machinist to oversee or repair the work station, plus the system supervisor. While the fixturing personnel in mechatronic environments require less advanced skills than corresponding workers in conventional factories, labour cost reduction is somewhat offset by the need for computing and other skills which may not be required in traditional workplaces (Hunt, 1988).

- *Reduced Work-in-Process Inventory and Lead Time:* The reduction of work-in-process in a mechatronic system is quite dramatic when compared to a job-shop environment. Reduction of 80 percent have been reported at some installations and may be attributed to a variety of factors including concentration of all the equipment required to produce parts into a small area; reduction in the number of fixtures required; reduction in the number of machines a part must travel through because processes are combined in work cells; and efficient computer scheduling of parts batched into and within the mechatronic system (Hunt, 1988).
- *Responsiveness to Changing Production Requirements:* We shall have to learn to live with complexity, dynamics and uncertainty of demand and supply conditions. Traditional automated systems are rigid and are not capable of responding rapidly to changes in demand and supply (Rzevski, 2003). A mechatronic system has the inherent flexibility to manufacture different products as the demands of the marketplace change or as engineering design changes are introduced (Hunt, 1988). Including the replacement of many mechanical functions with electronic ones, mechatronic systems and products exhibit certain distinguishing features by its inherent flexibility on easy redesign or reprogramming, the ability to implement distributed control in complex systems, and the ability to conduct automated data collection and reporting (Ashley, 2003). An automated mechatronic system is capable of handling materials and energy, communicating with its environment and is characterized by self-regulation, which enables it to respond to predictable changes in its environment (Rzevski, 2003).
- *High Product Quality:* A sometimes-overlooked advantage of a mechatronic system, especially when compared to machines that have not been federated into a cooperative system, is improved quality. The basic integration of product design characteristics with production capability, the high level of automation; the reduction in the number of fixtures and the number of machines visited, better designed permanent fixtures, and greater attention to part/machine alignment all

result in good individual part quality and excellent consistency from one work piece to another, further resulting in greatly reduced costs of rework (Hunt, 1988).

- *Operational Flexibility:* Traditional systems are limited in their flexibility in generating a wide variety of motions. Also restricted is their potential for creating complex functional relationships between the motion of the actuator and that of the driven element (Ashley, 2003). On the other hand, in some facilities, mechatronic systems can even run virtually unattended during the second and third shifts. This nearly unmanned mode of operation is currently the exception rather than the rule. It should, however, become increasingly common as better sensors and computer controls are developed to detect and handle unanticipated problems such as tool breakages and part-flow jams. In this operational mode, inspection, fixturing and maintenance can be performed during the first shift (Hunt, 1988).
- *Safety:* "Everybody initially was worried about the safety of electronics devices. I think people are now becoming aware that they are safer than mechanical ones", says Karl Hedrick, a mechanical engineer at the University of California, Berkeley. A large part of the reason they are safer is you can build in fault diagnoses and fault tolerances (Isermann, 2003).
- *Flexibility, functionality, accuracy and smartness:* The use of software applications in mechatronics products adds intelligence into seemingly dumb products. So does, the final systems and the products are flexible and have high functionality with respect to the ability to be adjusted for varying tasks. With the synergistic integration of a high performance control system can be much more precise and accurate such as it is in CNC machines and much more smarter while even being inexpensive such as it is in CD- and DVD-players, video recorders etc (abstracted from Amerongen, Breedveld, 2003; Amerongen, 2003; ATIP, 1998; McNamara, 2001).

7. ENGINEERING DESIGN

It is useful and common to divide the design process into the following main phases (See Figure 7.1):

- Planning and Clarifying the task
- Conceptual Design
- Embodiment Design
- Detail Design

It is not always possible to draw a clear boundary line between these main phases because each of these phases have a number of sub-phases and the starting input of the following phase is the output of the former phase. Within the main phases, there is going to be listed a number of operational working steps and at each of these main working steps, there are a number of lower level working steps through which some basic activities such as collecting information, searching for solutions, calculating, drawing, and evaluating are carried out. Some indirect activities such as discussing, classifying, and preparing accompanies these basic activities as well. After the main phases, or let's say, after these main working steps at each of the main phases, decision making steps are required. Through these decision making steps, the results of the main working steps within the phase and so the output of the main phase is evaluated. In the case that the results of decision making step are unsatisfactory, the some certain steps of the phase must be repeated. The smallest possible iteration loop is desirable. If the results are satisfactory, the following phase starts by receiving the output of former phase as the main input.

i. Planning and Clarifying the Task

To start a product development, a product idea is needed that looks promising given the current market situation, company needs and economic outlook. Not-

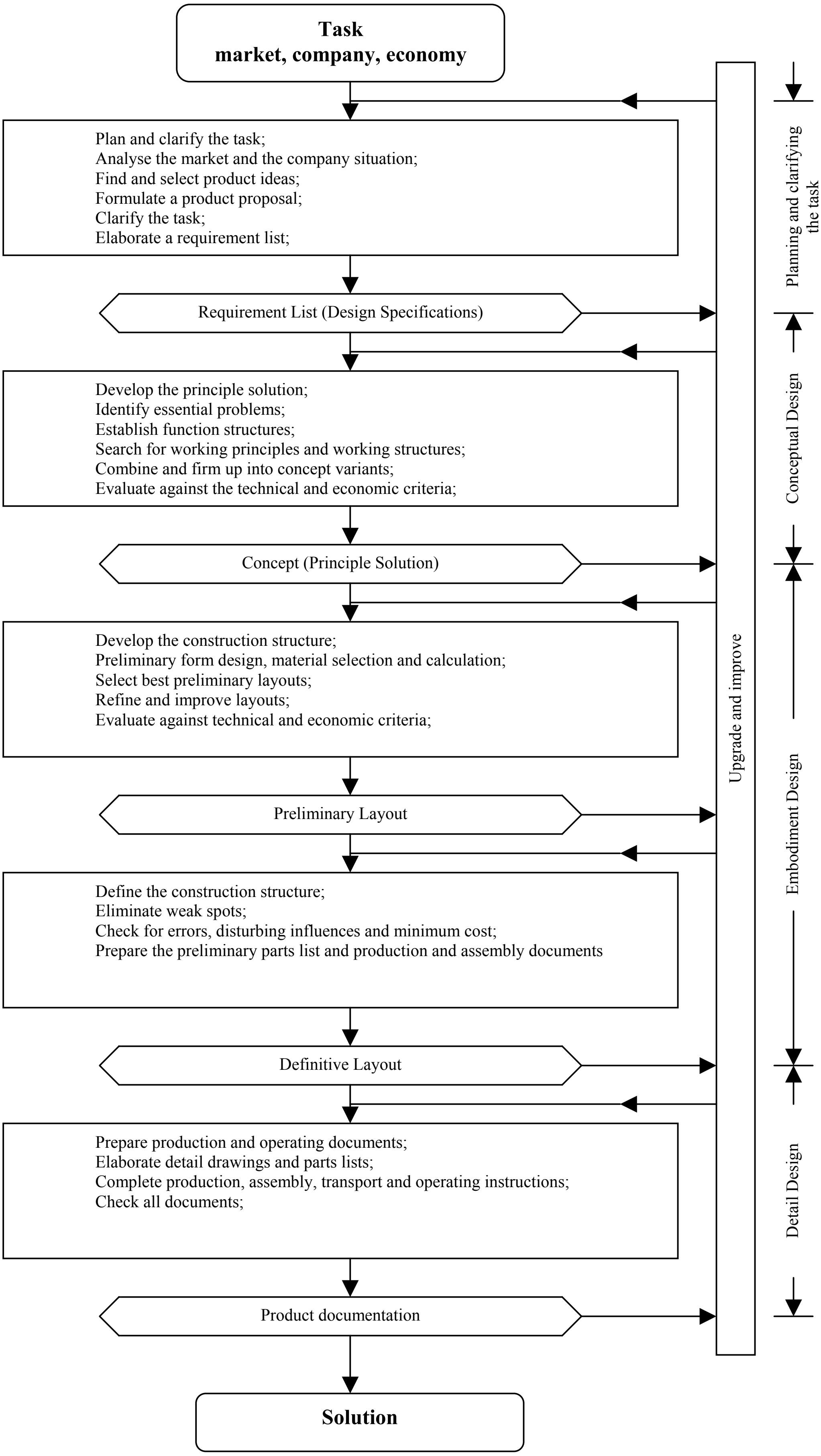


Figure 7.1 : Steps of Engineering design process (Pahl and Beitz, 1996)

withstanding the method, a successful product planning process always takes into account the market, the company and the economy. Several product ideas will be found and will need to be discussed in order to select suitable ones. The end result is a more *detailed product proposal*.

Irrespective of whether the task is based on the product proposal stemming from a product planning process or a specific customer order, it is necessary to clarify the given task in more detail before starting product development. The purpose of this *clarification of the task* is to collect information about the requirements that have to be fulfilled by the product, and also about the existing constraints and their importance.

This activity leads to the formulation of a *requirement list* that focuses on the interests of the design process and subsequent working steps. The conceptual design phase and subsequent phases must be based on this document which has to be updated continuously.

ii. Conceptual Design

After completing the task clarification phase, the conceptual design phase determines the principal solution. This is achieved by abstracting the essential problems, establishing function structures, searching for suitable working principles and then combining those principles into a working structure. Conceptual design results in the *specification of principle*.

Often, however, a working structure can not be assessed until it is transformed into a more concrete representation. This concretisation involves selecting preliminary materials, producing a rough dimensional layout, and considering technological possibilities. Only then, in general, is it possible to assess the essential aspects of a solution principle and review the objectives and constraints. It is possible that there will be several principle solution variants.

The representation of a principle solution can take many forms. For existing building blocks a schematic representation in the form of a function structure, a circuit diagram or a flow chart may be sufficient. In other cases a line sketch might be more suitable, and sometimes a rough scale drawing is necessary.

The conceptual design phase consists of several steps, none of which may be skipped if the most promising solution is to be reached. In the subsequent embodiment and detail design phases it is extremely difficult or impossible to correct fundamental shortcomings of the solution principle. A successful solution is more likely to come out from the choice of the most appropriate principles than from exaggerated concentration on technical details. This claim does not conflict with the fact that even in the most promising solution principles or combinations of principles problems may emerge during the detail design phase.

The solution variants that have been elaborated must now be evaluated. Variants that do not satisfy the demand of the requirements list have to be eliminated. The rest must be judged by the methodical application of specific criteria. On the basis of evaluation the best solution concept can now be selected. The design process now continues on a more concrete level referred to as embodiment design.

iii. Embodiment Design

During this phase, designers, starting from a concept (working structure, principle solution), determine the construction structure (overall layout) of a technical system in line with technical and economic criteria. Embodiment design results in the *specification of layout*.

It is often necessary to produce several preliminary layouts and scale drawings simultaneously or successively in order to obtain more information about the advantages and disadvantages of the different variants.

After sufficient elaboration of the layouts, this design phase also ends with an evaluation against technical and economic criteria. Frequently, the evaluation of individual variants may lead to the selection of one that looks particularly promising but which may nevertheless benefit from and further improved by incorporating ideas and solutions from the others. By the appropriate combination and the elimination of weak links, the best layout can then be obtained.

That definitive layout provides a check of function, strength, spatial compatibility etc., and it is also at this stage, at the very latest, that the financial viability of the project must be assessed. Only then should work start on the detail design phase.

iv. Detail Design

This is the phase of the design process in which the arrangement, forms, dimensions, and surface properties of all the individual parts are finally laid down, the material specified, production possibilities assessed, costs estimated and all the drawings and other production documents produced. Quite often corrections must be made during this phase and the preceding steps repeated for the improvement of assemblies and components. The crucial activities are:

- optimisation of the principle;
- optimisation of the layout, forms and material;

and

- optimisation of the production.

7.1 Product Planning and Clarifying the Task

7.1.1 Product Planning

Before a commercial product can be designed there has to be a product idea which promises to lead to a technically and economically viable product. That is not necessary if the task comes directly from a client but otherwise product planning is always the first step in product design. Through the product planning phase, a systematic search is carried out in order to select and develop promising product ideas (See Figure7.2).

The basis and the starting point for product planning is marketing. Marketing provides an interface between the customers and the company. They carry the voice of the customers to the company and the offers of the company to the market, to the customers. The basic goal of a company which is operating in a consumer market is to keep alive its competitive advantage by better fulfilling the customer requirements. All disciplines within the company have to contribute to this basic goal. Marketing;

alongside product planning, design, production and sales, monitors the fulfilment of customer requirements and act as the agent of the customer within the company. The stimuli for product plans may come from outside, that is, from the market and other sources (new product through market pull) or from inside, that is, from the company itself (new product through technology push).

Stimuli from the market and other sources include:

- the technical and economic position of the company's products in the market, in particular when changes occur, such as a reduction in turnover or a drop in market share;
- changes in market requirements, for example new functions or fashions;
- suggestions and complaints of customers;
- technical and economic superiority of competing products;
- economic and political changes, for example oil price increases, resource shortages, transport restrictions;
- new technologies and research results, for example micro-electronic replacing mechanical solutions or laser cutting replacing flame cutting and environmental and recycling issues

Stimuli from within the company include:

- new ideas and results of company's researches applied in development and production.
- new functions to extend or satisfy the market;
- introduction of new production methods;
- rationalization of product range and production; and
- increasing degree of product diversification, which is a range of products with life cycles that are planned to overlap.

These external and internal stimuli initiate five main working steps that will be discussed in more details below.

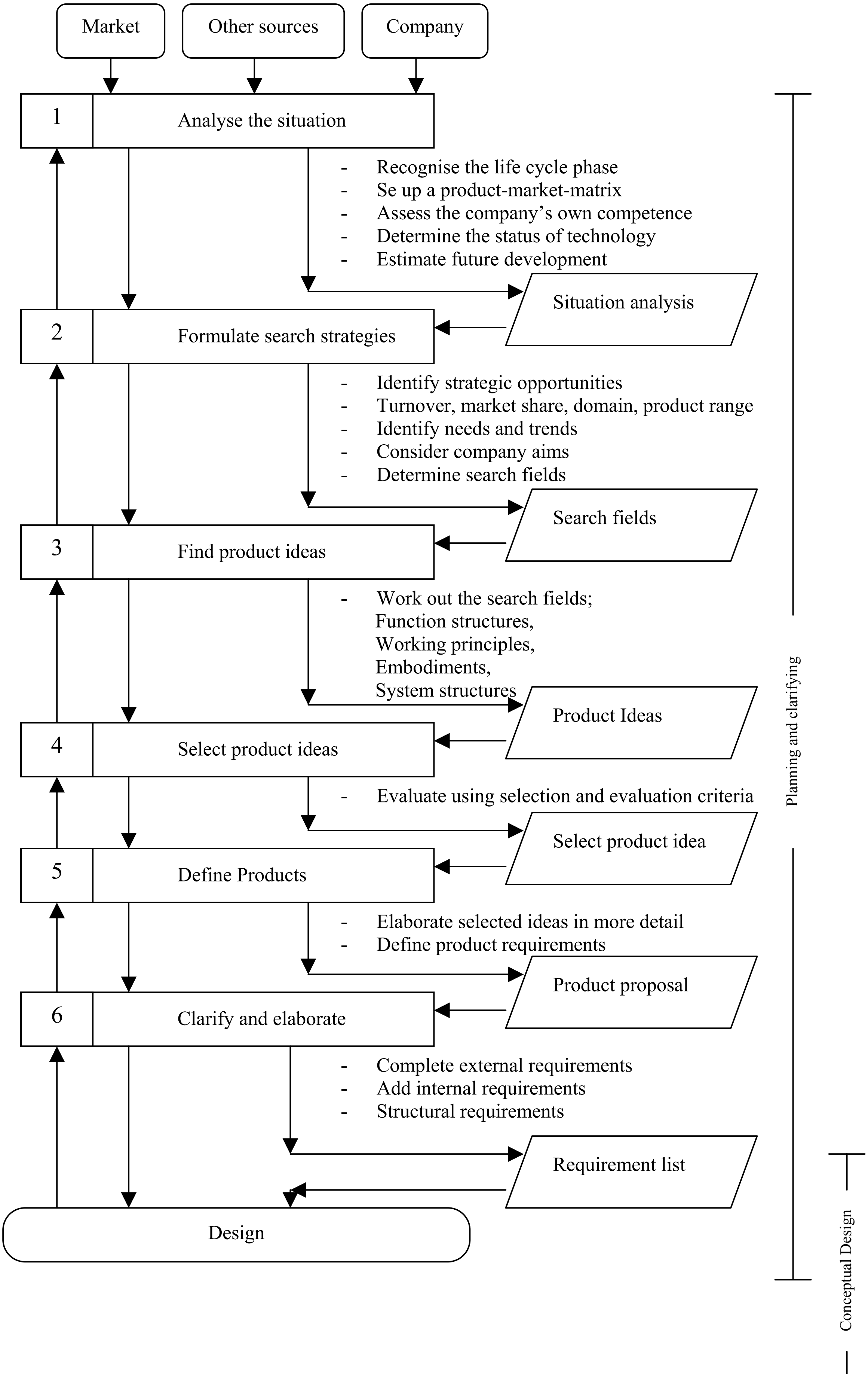


Figure 7.2: Procedures for product planning and clarifying the task (Pahl and Beitz, 1996)

7.1.1.1 Analysing the Situation

Situation analysis of the company and its products is carried out through a number of activities using the knowledge from the market and the other sources.

Recognising the life-cycle phase: Every product has a life-cycle which can generally be exhibited with a turnover/time schedule as it is shown in Figure 7.3. The saturation phase triggers the introduction of new products. Till the time that life-cycle reaches to the saturation phase, at the latest, new products have to be developed and introduced to the market. In order to be able to manage that process, product monitoring is very important.

Setting up a product-market-matrix: Recognising and clarifying the status of existing products from the company and from competitors in the various market segments with respect to turnover, profit and market share should reveal the strengths and weaknesses of each of the products. Under the lights of this information, place of company's current products can be defined within the product market matrix. A comparison with strong competitors is of particular interest.

Assessing the company's own competence: This part of the analysis extends the previous one. It provides the reasons for the current market position through an

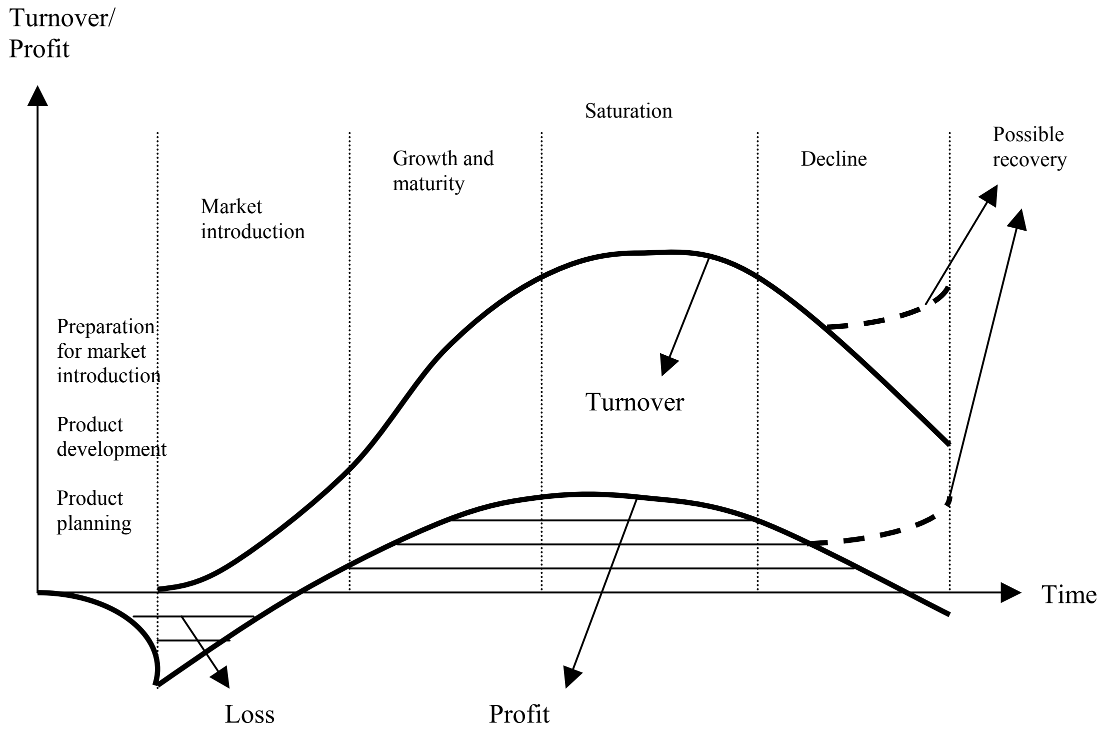


Figure7.3: Life cycle of a product(Pahl and Beitz, 1996)

assessment of the company’s technical weaknesses and a comparison with competing companies.

Determining the status of technology: This includes the reviewing the company’s products with respect to the related technologies, concepts and products in the literature and patents, as well as competitors’ products. In addition, the latest standards guidelines and regulations are important.

Estimating future developments: Guidance can be obtained from knowledge of future projects, expected customer behaviour, technological trends, environmental requirements and the results of fundamental search.

Situation analysis determines the search strategies and the search fields that have to be addressed.

7.1.1.2 Formulating Search Strategies

Identifying strategic opportunities: It is possible that during the situation analysis some gaps in the current product range or in the market are identified. The task now is to determine which strategy to adopt; to introduce new products into the current market; to open new markets with existing products; or even to enter into new markets with new products. The latter includes the highest risk.

Identify needs and trends: The most important thing for determining search fields is the identification of customer needs and market trends. Clues for this come from changing customer behaviour caused, for example, by social developments such as environmental awareness, disposal problems, reduction in working week, and transport problems. A further starting point can be changes in manufacturing supply chain which can lead to new markets for suppliers.

Considering company aims: Table 7.1 lists the aims and strengths of the company which have to be used to select a search field.

Determining search fields: The previously described steps of this product planning stage should lead, after a selection process, to a limited number of search fields on which to concentrate the further search for products.

Table:7.1 Decision Criteria for product planning *(Pahl and Beitz, 1996)*

Criteria	weights
Company goals	≥ 50%
Adequate financial cover	
High turnover	
High market growth	
Large market share	
Short-term market opportunity	
Large functional advantages for users and excellent quality	
Differentiation from competitors	
Company strengths	≥ 30%
Extensive know-how	
Favourable extension to range and/or product programme (diversification)	
Strong market position	
Limited need for investment	
Few sourcing problems	
Favourable nationalisation potential	
Market and other sources	≥ 20%
Low danger of substitution	
Weak competition	
Favourable patent status	
Few general restrictions	

7.1.1.3 Finding Product Ideas

The preferred search fields are now investigated in more detail using known search methods such as conventional methods (literature search, analysis of natural systems, analysis of existing technical systems, analogies, measurements and model tests), intuitive methods (brainstorming, method 635, gallery method, Delphi method, synectics), or discursive methods (systematic study of physical processes systematic search with the help of classification schemes, use of design catalogues) (see Pahl and

Beitz, 1996, section 4.1, for more detail). Depending on the degree of novelty, the starting point for new products can be new product functions, other working principles, new embodiments, and rearrangements of an existing or new system structure. The considerations follow the known interrelationship between function, working principle and embodiment:

Function:

- Which function does the client require?
- Which functions do we already fulfil?
- What complements existing functions?
- Which functions represent a generalisation of the exiting ones?

Working principle:

Existing products are based on a specific working principle. Would a change of working principle lead to better products? Characteristics to look for are the types of energy and physical effects.

Embodiment:

- Is the space used still appropriate?
- Should we focus on miniaturization?
- Is the shape still appealing?
- Could the ergonomics be improved?

7.1.1.4 Selection of Product Ideas

The product ideas generated are first subjected to a selection procedure. For this initial selection, the criteria linked to the company's goals are sufficient. At the very least, high turnover, large market share and functional advantages for the customer should be taken into account.

For the systematic approach, the solution field should be as wide as possible. Later on, these great numbers of solutions must be reduced at the earliest possible time. On the other hand, care must be taken in order not to eliminate valuable working principles, because often it is only through their combination with others that an advantageous working structure will emerge.

Selection procedure involves two steps, namely elimination and preference. First, all unsuitable proposals are eliminated. If too many possible solutions still remain, those which are patently better than the rest must be given preference. Only these solutions are further elaborated and evaluated. If faced with a large number of solution proposals, the designer should compile a selection chart (see Pahl and Beitz, 1996, section 4.2.1, for more detail). First of all, an evaluation for each of the proposals through following questions is made for elimination.

- Is this proposal compatible with its overall task (Criterion A)?
- Does it fulfil the demands of the requirements list (Criterion B)?
- Is it reasonable in respect of performance, layout etc. (Criterion C)?
- Is it expected to be within permissible cost (Criterion D)?

Unsuitable solutions are eliminated in accordance with these four criteria applied in the correct sequence. Criteria C and D should only be used once A and B have been satisfied.

If there still remain a number of possible solutions, a preference is justified for the proposals which:

- incorporate direct safety measures or introduce favourable ergonomic conditions (Criterion E);
- are preferred by the designer’s company, that is, can be readily developed with the available know-how, materials, and procedures, and under favourable patent conditions (Criterion F);

Additional selection criteria can be used if they are helpful in coming to a decision.

7.1.1.5 Product Definition

In this step product ideas that seem promising are elaborated more concretely and in more detail. During this step, sales, marketing, research, development and design people should work actively together. Product ideas, after elaboration, are then subjected to an evaluation and the best product definitions are given to the product development department as a product proposal together with a preliminary requirement list.

The product proposal should:

- describe the intended functions.
- contain a preliminary requirement list that should have been compiled as far as possible using the headings that are used later on during product development to clarify the task and finalise the requirement list.
- formulate all requirements. The working principle should only be determined in so far as it is really necessary from the point of view of the overall functionality.
- Indicate a cost target or a budget linked to the company's goals which clarifies future intentions such as production volume, extensions to product range, new suppliers, etc.

This concludes the product planning phase.

7.1.2 Clarifying the Task

The work of designers starts with a particular problem. Every task involves certain constraints that may change with time but must be fully understood if the optimum solution is to be found. Whether or not this phase has been preceded by product planning, resulting in a preliminary requirement list, designers must still define the task as fully and clearly as possible so that amplifications and corrections during its subsequent elaboration can be confined to the most essential. To that end, and also as a basis for subsequent decisions, a requirement list should always be drawn up and consulted.

The task is generally presented to the design or development department in one of the following forms:

- as a development order (from outside or from the product planning department in the form of a product proposal);
- as a definite order; or
- as a request based on, for instance, suggestions and criticisms by sales, research,, test or assembly staff, or origination in the design department itself.

Without close contact between the client on the one hand and those in charge of the design department on the other, no optimum solution can be expected because the problem, as presented to the design department, often does not contain all the necessary information. A phase of further data collection must than be initiated. This phase must answer the following questions:

- What is the problem really about?
- What implicit wishes and expectations are involved?
- Do the specified constraints actually exist? And
- What paths are open for development?

Fixed solution ideas or concrete indications which are implicit in the task formulation often have an adverse effect on the final outcome. Only the required function with the appropriate inputs and outputs and the task-specific constraints should be specified right at the start. For that purpose the following questions must be asked:

- What objectives is the intended solution expected to satisfy?
- What properties must it have? and
- What properties must it not have?

After all the necessary data have been collected, a requirement list should be drawn up which is more detailed than the one supplied by the client or the product planning group.

When preparing a detailed requirement list it is essential to state whether the individual items are demands or wishes. *Demands* are requirements which must be met under all circumstances, in other words, these are requirements without whose fulfilment the solution is not acceptable. *Wishes* are requirements which should be taken into consideration whenever possible. It is advisable to classify wishes as being of major, medium or minor importance. The distinction between demands and wishes is also important at the evaluation stage, since selection depends on the fulfilment of demands. For further information about the requirement list see Pahl and Beitz, 1996, section 5.2.2.

7.2 Conceptual Design

Conceptual design is that part of design process in which the basic solution path is laid down through the elaboration of a solution principle. In this phase, the essential problems are identified through abstraction; appropriate working principles and their combinations are searched; and the final function structures are established. Just before starting the phase, following questions must be answered:

- Has the task been clarified successfully to allow development of a solution in the form of a design?
- Must further information about the task be acquired?
- Is it possible to reach the chosen objective within the given financial restrictions?
- Is a conceptual elaboration really needed, or do known solutions permit direct progress to the embodiment and detailed design phases?
- If the conceptual stage is indispensable, how and to what extent should it be developed systematically?

Having a well prepared requirement list which is the result of product planning and clarification of the task phase and the answers of above questions in mind, conceptual design starts with following steps (see Figure7.4).

7.2.1 Abstracting to Identify the Essential Problems

Every industry and every design office is a store of experiences as well as of prejudices and conventions which, coupled to the wish to minimise risks, stand in the way of better and more economic but unconventional solutions. The client, customer or product planning group might have included specific proposals for a solution in the requirements list. It is also possible that during the discussion of individual requirements, some ideas and suggestions for realising a solution may emerge. Even in the unconscious, at least, certain solution might exist (fixation). In their search for optimum solutions, designers, far from allowing themselves to be influenced by such fixed and conventional ideas, must examine very carefully all the suitable paths which go to the optimal solution. To solve the problem of fixation and sticking with conventional ideas, *abstraction* is used. This means ignoring what is particular or identical and emphasizing what is general and essential.

The first step of abstraction is to analyse the requirements list in respect of the required functions and essential constraints to establish the crux of the problem. The functional relationships contained in the requirements list must be formulated explicitly and arranged in order of their importance. Following steps are carried out in order to abstract the essential requirements:

i. Eliminate personal preferences.

ii. Omit requirements that have no direct bearing on the function and the essential constraints.

iii. Transform quantitative into qualitative data and reduce them to essential statements.

iv. Generalise the results of the previous step.

v. Formulate the problem in solution neutral terms.

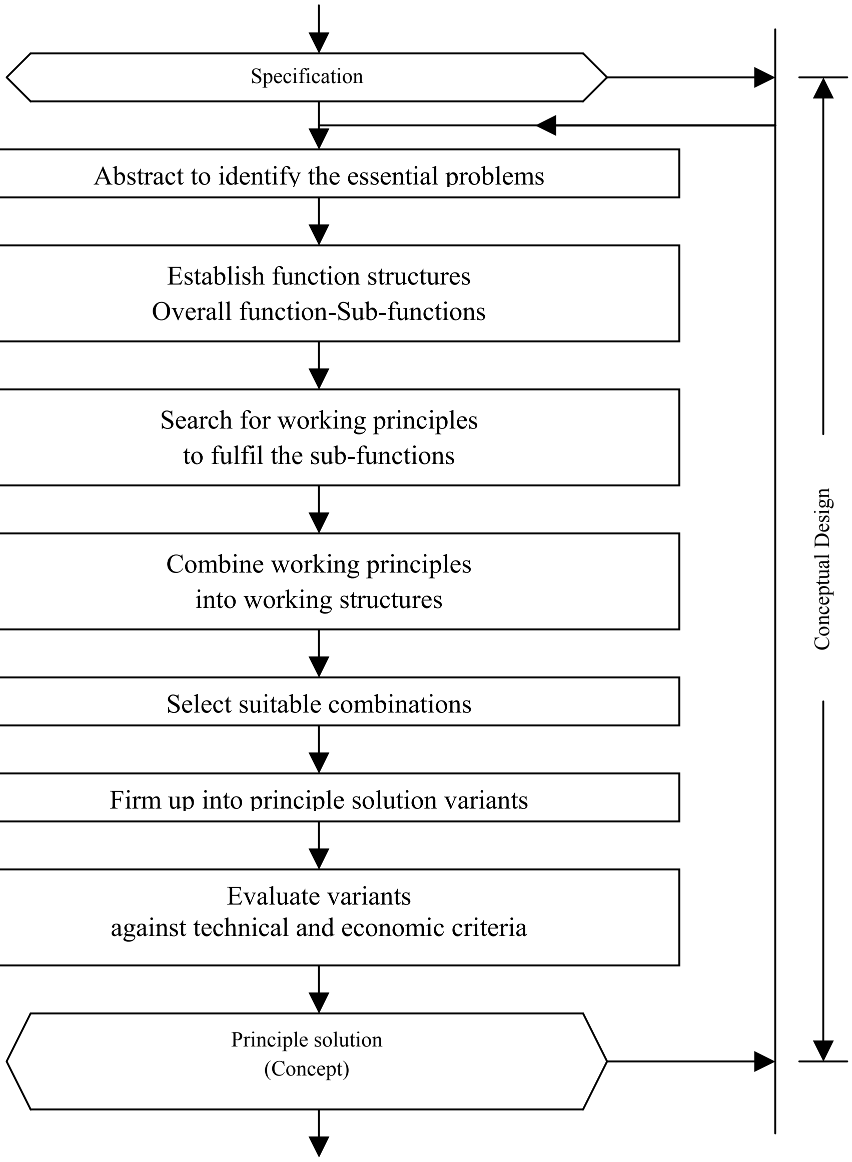


Figure 7.4: Steps of Conceptual Design (Pahl and Beitz, 1996)

Depending on either the nature of the task or the size of the requirement list, or both, certain steps may be omitted. This analysis thus leads to a definition of the objective on an abstract plane without laying down any particular solution.

Once the crux of the task has been identified by correct problem formulation, a step by step enquiry must be initiated to discover if an extension of or even a change in the original task might lead to promising solutions.

7.2.2 Establishing Function Structures

a. Overall Function

Once the crux of the overall problem has been formulated, it is possible to indicate an overall function that, based on the flow of energy, material and signals can, with the use of a block diagram, express the relationship between inputs and outputs independently of the solution. This relationship must be specified as precisely as possible.

b. Breaking Down into Sub-functions

Depending on the complexity of the problem, the resulting overall function will be more or less complex. The complexity here means the relative lack of transparency of the relationships between inputs and outputs, the relative intricacy of the necessary physical processes, and the relative large number of assemblies and components involved.

Just as a technical system can be divided into subsystems and elements, a complex overall function can be broken down into sub-functions of lower complexity as well. The combination of individual sub-functions results in a function structure representing the overall function.

The purpose of breaking down complex functions is:

- the determination of sub-functions facilitating the subsequent search for solutions; and
- the combination of these sub-functions into a simple and unambiguous function structure.

The optimum method of breaking down an overall function - that is, the number of sub-function levels and also the number of sub-functions per level – is determined by the relative novelty of the problem and also by the method used to search for a solution.

c. Practical Uses of Function Structures

When establishing function structures, we must distinguish between original and adaptive designs. In the case of *original designs*, the basis of a function structure is the requirements list and the abstract formulation of the problem. Among the demands and wishes, we are able to identify functional relationships, or at least the sub-functions between the inputs and outputs of a function structure. In the case of adaptive designs, the starting point is the function structure of the existing solution obtained by the analysis of the elements. It helps to develop variants so as to open the path for other solutions, for subsequent optimisation and to develop modular products.

Anyone setting up a function structure ought to bear the following points in mind:

1. First derive a rough function structure with a few sub-functions from what functional relationships you can identify in the requirements list and then break this rough structure down, step by step, by the resolution of complex sub-functions.
2. If no clear relationship between the sub-functions can be identified, the search for the first solution principle may be based on the mere enumeration of important sub-functions without logical or physical relationships, but if possible, arranged according to the extent to which they have been realised.
3. Logical relationships may lead to some function structures through which the logical elements of various working principles (mechanical, electrical etc.) can be anticipated.
4. Function structures are not complete unless the existing or expected flow of energy, material and signals can be specified. Nevertheless, it is useful to begin by focusing attention on the main flow because, as a rule, it determines the design and is more easily derived from the requirements. The auxiliary flows then help in the further elaboration of the design, in coping with faults, and in dealing with problems of power transmission, control etc. The

complete function structure, comprising all flows and their relationships, can be obtained by iteration, that is, by looking first for the structure of main flow, completing that structure by taking the auxiliary flows into account, and then establishing the overall structure.

5. In setting up function structures it is helpful to know that, in the conversion of energy, material and signals, several sub-functions recur in most structures and should therefore be introduced first.
6. For the application of microelectronics, it is useful to create signal flows in the function structure by modular use of elements such as to detect (sensors), to activate (actuators), to operate (controllers), to indicate (displays) and , in particular, to process signals using microprocessors.
7. From a rough structure, or from a function structure obtained by the analysis of known systems, it is possible to derive further variants and hence to optimise the solution, by:
    - breaking down or combining individual sub-functions;
    - changing the arrangement of individual sub-functions;
    - changing the type of switching used;
    - shifting in the system boundary.

    Because varying the function structure introduces distinct solutions, the setting up of function structures constitutes a first step in the search for solutions.
8. Function structures should be kept as simple as possible, so as to lead to simple and economical solutions.
9. In the search for solution, none but promising function structures should be introduced, for which purpose a selection procedure should be employed, even at this early stage.
10. For the representation of function structures it is best to use the simple and informative symbols shown in Figure 7.5, supplemented with task-specific verbal clarifications.

11. An analysis of the function structure leads to the identification of those sub-functions for which new working principles have to be found, and of those for which known solutions can be used.

Function structures are intended to facilitate the discovery of solutions: they are not ends in themselves. It depends very much on the novelty of the task and the experience of designers to what degree they are detailed.

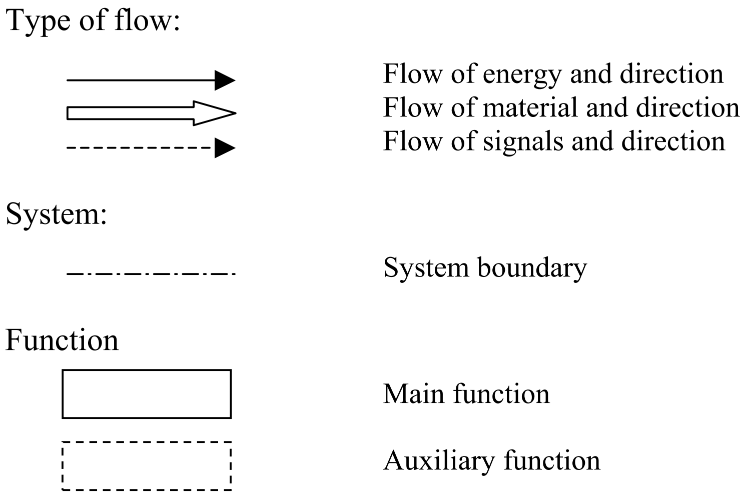


Figure 7.5: Symbols for representing sub-functions in a function structure (Pahl and Beitz, 1996)

7.2.3 Developing Working Structures

a. Searching for Working Principles

Working principles have to be found for the various sub-functions and these principles must eventually be combined into a working structure. The concretisation of the working structure will lead to the solution principle. A working principle must reflect the physical effect needed for the fulfilment of a given function and also its geometric and material characteristics.

As it is declared earlier there are several, known search methods and tools for finding solutions such as conventional methods (literature search, analysis of natural systems, analysis of existing technical systems, analogies, measurements and model tests), intuitive methods (brainstorming, method 635, gallery method, Delphi method, synectics), and discursive methods (systematic study of physical processes systematic search with the help of classification schemes, use of design catalogues) (see Pahl and

Beitz, 1996, section 4.1, for more detail). In the search for working principles the same methods can be used. Of particular importance, however, are literature search, methods for analysing natural and known technical systems, and intuition-based methods. If preliminary solution ideas are available from product planning or through intuition, the systematic analysis of physical processes and the use of classification schemes are also helpful. Other important tools are design catalogues.

b. Combining Working Principles

To fulfil the overall function, it is now necessary to elaborate overall solutions for the combination of principles, that is, system synthesis is now necessary. The basis of such combinations is the established function structure which reflects logically and physically possible or useful associations of the sub-functions.

The main problem with such combinations is ensuring the physical and geometric compatibility of the working principles to be combined, which in turn ensures the smooth flow of energy, material and signals. A further problem is the selection of technically and economically favourable combinations of principles from the large field of technically possible combinations.

For systematically combining solutions, the classification scheme of Zwicky (see Pahl and Beitz, 1996, section 4.1.4, for more detail) is particularly suitable. In this classification scheme the sub-functions and the appropriate solutions (working principles) are entered in the rows of the scheme. By combining a working principle fulfilling a specific sub-function with the working principle for a neighbouring sub-function one obtains an overall solution in the form of a possible working structure. In this process only those working principles that are compatible should be combined.

Combining solutions by using mathematical methods (see Pahl and Beitz, 1996, section 4.1.4, for more detail) is only possible for working principles whose properties can be quantified. However, this is seldom possible at this early stage.

To sum up:

- Only combine compatible sub-functions
- Only pursue such solutions as meet the demands of the requirements list and look like falling within the proposed budget.

- Concentrate on promising combinations and establish why these should be preferred above the rest.

c. Selecting Suitable Working Structures

Because working structures are in general not very concrete and the properties are only known qualitatively, the most suitable selection procedure here is the one which is made by the use of a selection chart which includes solution variants on the rows and selection criteria on the columns and makes the selection through elimination and preference (see Pahl and Beitz, 1996, section 4.2.1 and 6.4.3, for more detail). This selection procedure involves two steps, namely elimination and preference. First, all totally unsuitable proposals are eliminated. If too many possible solutions still remain, those which are patently better than the rest must be given preference. Within the selection criteria are:

- Compatibility of solution variant against the other solutions and within the overall task
- Fulfilment of demands of requirements list
- Eligibility in respect of performance, layout etc.
- Cost effectiveness

7.2.4 Developing Concepts

a. Firming up into Principle Solution Variants

The principles elaborated in 7.2.3 are usually not concrete enough to lead to the adoption of a definite concept. This is because, as the search for a solution is based on the function structure, it is aimed at the fulfilment of a technical function. A concept must, however, also satisfy the conditions such as safety, ergonomics, production, quality, assembly, transport, handling, maintenance, recycling, cost effectiveness etc.

The selection process may already have revealed gaps in information about very important properties, sometimes to such an extent that not even a rough and ready decision is possible. The most important properties of the proposed combination of principles must first be given a much more concrete qualitative and often also a rough quantitative definition. Important aspects of working principle and also of the embodiment and finally of important task-specific constraints must be known, at least approximately. More detailed information need only be gathered for promising combinations. If necessary, a second or third selection must follow the collection of further information.

The necessary data are essentially obtained with the help of such proven methods as:

- rough calculations based on simplified assumptions;
- rough sketches or rough scale drawings of possible layouts, forms, space requirements, etc.;
- preliminary experiments or model tests to determine the main properties, or approximate quantitative statements about the performance and scope for optimisation;
- construction of models to aid analysis and visualization;
- analogue modelling and systems simulation, often with the help of computers;
- further searches of patents and the literature with narrower objectives; and
- market research of proposed technologies, materials, etc.

With these fresh data it is possible to firm up the most promising combinations of principles to the point at which they can be evaluated. The properties of the variants must reveal technical and economic features so as to permit the most accurate evaluation possible.

b. Evaluating Principle solution Variants

For the evaluation of principle solution variants the following steps are recommended:

i. *Identifying evaluation criteria*

This step is based, first of all, on the requirements list. During a previous selection procedure (7.2.3 c) unfulfilled demands may have led to the elimination of variants that were found to be unsuitable in principle. Further information was gathered subsequently by firming up into principle solutions. Hence it is advisable, with all the newly acquired information, to establish first of all whether all the proposals to be evaluated still satisfy the demands of the requirements list. This can involve a new yes/no decision- that is a new selection.

At the given state of information, it may only be possible to decide how likely it is that certain requirements can be fulfilled. In that case, the requirements in question may become evaluation criteria.

For evaluation during the conceptual phase, both the technical and also the economic characteristics should be considered as early as possible. At the firming up stage, however, it is not usually possible to give the costs in figures. Nevertheless, the economic aspects must be taken into consideration, at least qualitatively, and so must industrial and environmental safety requirements. Hence, it is necessary to consider technical, economic and safety criteria at the same time. It is suggested that the evaluation criteria are derived from the main headings in Table 7.2.

ii. *Compiling Parameters*

It is useful to list the identified criteria in the sequence of the check list headings and to assign the parameters of the variants to them. Whatever quantitative information is available at this stage should also be included.

iii. *Assessing Values*

Although it is difficult to make clear assessments because of lack of information at this stage, it is not advisable to evaluate too timidly during the conceptual phase. At this point, some values, points are appointed to the solution variants depending on the range of assessment. For example, use-value analysis employs a range from 0 to 10; Guideline VDI 2225 a range from 0 to 4 (see Pahl and Beitz, 1996, section 4.2.2 for more detail). The advantage of the wider range is that classification and evaluation are greatly facilitated. The advantage of the smaller range is that, in dealing with inadequately known characteristics of the variants, rough eliminations are sufficient and, indeed, may be the only meaningful approach.

iv. Determining Overall Value

The determination of the overall value is a matter of simple addition, once points have been assigned to the evaluation criteria and the variants.

Table7.2 : Checklist with main headings for design evaluation during the conceptual phase (Pahl and Beitz, 1996)

Main Headings	Examples
Function	Characteristics of essential auxiliary function carriers that follow of from the necessary solution principle or from the concept variant
Working Principle	Characteristics of the selected principle or principles in respect of simple and clear-cut functioning, adequate affect, few disturbing factors
Embodiment	Small number of components, low complexity, low space requirement, no special problem with layout or form design
Safety	Preferential treatment of direct safety techniques (inherently safe), no additional safety measures needed, industrial and environment safety guaranteed.
Ergonomics	Satisfactory man-machine relationship, no strain or impairment of health, good aesthetics
Production	Few and established production methods, no expensive equipment, small number of simple components
Quality Control	Few tests and checks needed, simple and reliable procedures
Assembly	Easy, convenient and quick, no special aid needed
Transport	Normal means of transport, no risks
Operation	Simple operation, long service life, low wear, easy and simple handling
Maintenance	Little and simple upkeep and cleaning, easy inspection, easy repair
Recycling	Easy recovery of parts, safe disposal
Costs	No special running or other associated costs, no scheduling risks

v. Comparing Concept Variants

A relative value scale is generally more suitable for purposes of comparison. In particular, it makes it fairly simple to tell whether particular variants are relatively close to or far from the target. Concept variants that are 60 percent below the target are not worth further development.

Variants with ratings above 80 percent and a balanced value profile – that is, without extremely bad individual characteristics – can generally be moved on to the embodiment design phase without further improvement. Intermediate variants, too, may, after the elimination of weak spots or an improved combination, be released for embodiment design.

vi. *Estimating Evaluation Uncertainties*

This step is very important, especially during conceptual phase, and must not be omitted. Evaluation methods are mere tools, not automatic decision mechanisms. Uncertainties must be determined. At this point, however, only such information gaps need be closed as bear on the best concept variants.

vii. *Searching for Weak Spots*

During the conceptual phase, the value profile plays an important role. Variants with a high rating but definite weak spots (unbalanced value profile) may prove extremely troublesome during subsequent development. If, because of an unidentified evaluation uncertainty, which is more likely to occur in the conceptual than in the embodiment phase, a weak spot should make itself felt later, then the whole concept may be put in doubt and the development work may prove to have been in vain. In such cases it is very much less risky to select a variant with a slightly lower rating but a more balanced value profile.

Weak points in favourite variants can often be eliminated by the transfer better sub-solutions from other variants.

7.3 Embodiment Design

7.3.1 Steps of Embodiment Design

Having elaborated the principle solution during the conceptual phase, the underlining ideas can now be firmed up. During the embodiment phase, at the latest, designers must determine the overall layout design, the preliminary form designs and the production processes, and provide solutions for any auxiliary functions. In many cases several embodiment designs are needed before a definitive design appropriate to the desired solution can emerge (See Figure 7.6).

It is always advisable to proceed from the qualitative to the quantitative, from the abstract to the concrete, and from rough to detailed designs, and to make provision for checks and, if necessary, for corrections.

1. Using the requirement list, the first step is to identify those requirements that have a crucial bearing on the embodiment design;
    a. Size-determining requirements such as output, through-put, size of connectors,
    b. Arrangement-determining requirements such as direction of flow, motion, position etc, and
    c. Material-determining requirements such as resistance to corrosion, service life, special material etc.

Requirements based on safety, ergonomics, production and assembly involve special design considerations which may affect the size, arrangement and selection of materials

2. Scale drawings of spatial constraints determining or restricting the embodiment design must be produced (for instance drawings showing clearances, axle positions, installation requirements, etc).
3. Once the embodiment-determining requirements and spatial constraints have been established, a rough layout, derived from the concept, is produced with the emphasis on the embodiment-determining main function carriers, that is, the assemblies and components fulfilling the main functions.
4. Preliminary layouts and form designs for the embodiment-determining main function carriers must be developed; that is, the general arrangement, component shapes and materials must be determined provisionally. The result must meet the overall spatial constrains and then be completed so that all the relevant main functions are fulfilled. Known solutions or existing components must be shown in simplified form. It may be useful to start working on selected areas only, combining these later into preliminary layouts.
5. One or more suitable preliminary layouts must be selected in accordance with the preliminarily explained procedures.
6. Preliminary layouts and form designs must now be developed for the remaining main function carriers that have not yet been considered because known solutions exist or they are not embodiment-determining until this stage.

7. Next, determine what auxiliary essential functions (such as support, retention, sealing and cooling) are needed and, where possible, exploit known solutions (such as repeat parts, standard parts, catalogue solutions). If this proves impossible, search for special solutions.
8. Detailed layouts and form designs for the main function carriers must know be developed in accordance with the embodiment design rules and guidelines, with the attention to standards, regulations, detailed calculations and experimental findings, and also to the problem of compatibility with those auxiliary functions that have now been solved. If necessary, divide into assemblies or areas that can be elaborated individually.
9. Proceed to develop the detailed layouts and form designs for the auxiliary function carriers, adding standard and bought-out parts. If necessary, refine the design of main function carriers and combine all function carriers into overall layouts.
10. Evaluate the layouts against technical and economic criteria.
11. Fix the preliminary layout.
12. Optimise and complete the form designs for the selected layout by elimination of the weak points that have been identified in the course of the evaluation. If it should prove advantageous, repeat the previous steps and adopt suitable sub-solutions from less favoured variants.
13. Check this layout design for errors (design faults) in function, spatial compatibility etc and for the effects of disturbing factors. Make what improvements may be needed. The achievement of the objectives with respect to the cost and quality must be established at this point at the latest.
14. Conclude the embodiment design phase by preparing a preliminary parts list and preliminary production and assembly documents.
15. Fix the definitive layout design and pass on to the detail design phase.

In the embodiment phase, unlike the conceptual phase, it is not necessary to lay down special methods for every individual step. To sum up, embodiment design involves a flexible approach with many iterations and changes of focus. The individual steps have to be selected and adapted to the particular situation. While pay-

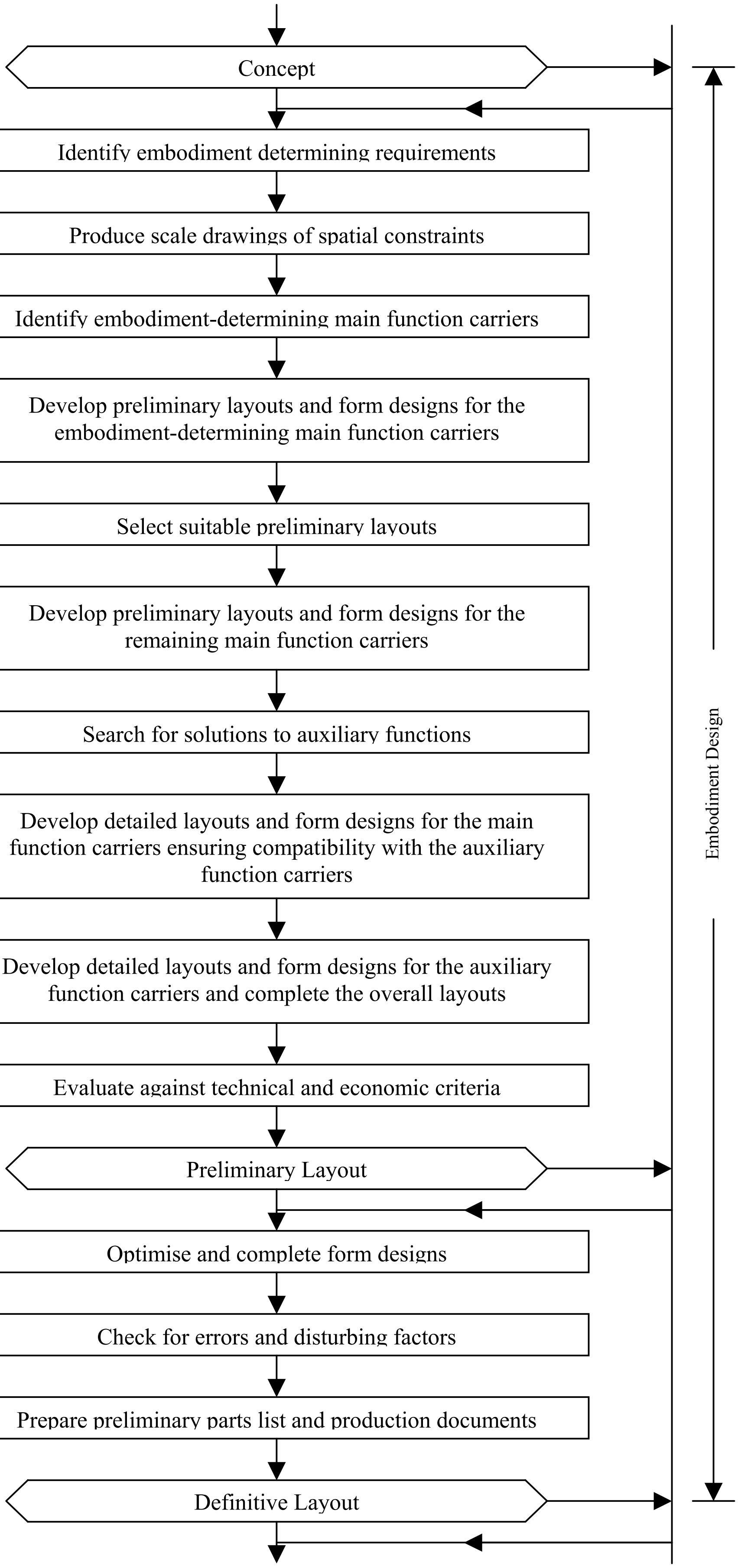


Figure 7.6 : Steps of Embodiment Design (Pahl and Beitz, 1996)

ing due regard to the fundamental links between the steps and recommendations explained above, the ability to organise one's own approach is important.

7.3.2 Checklist for Embodiment Design

Every embodiment design is an attempt to fulfil a given function with appropriate layout, component shapes and materials. The process starts with preliminary scale layout drawings based on spatial requirements and a rough analysis, and proceeds to consider safety, ergonomics, production, assembly, operation, maintenance, recycling and costs.

In dealing with these factors, designers will discover a large number of interrelationships, so that their approach must be progressive as well as iterative. Though individual factors may be closely interrelated, designers can derive important checklist headings from the general objectives and constraints which provide them with a useful procedural order and systematic check on each step (See Table 7.3). The checklist thus not only provides a strong mental impetus, but also ensures that nothing essential is forgotten in the embodiment phase.

7.3.3 Basic Rules of Embodiment Design

There are three basic rules of embodiment design such as clarity, simplicity and safety, which are derived from the general objectives, that is:

- fulfilment of the technical function;
- economic feasibility; and
- individual and environmental safety.

Clarity, that is clarity of function or the lack of ambiguity of a design, facilitates reliable prediction of the performance of the end product and in many cases saves time and costly analyses.

Simplicity generally guarantees economic feasibility. A smaller number of components and simple shapes are produced more quickly and easily.

Safety imposes a consistent approach to the problems of strength, reliability, accident prevention and protection of the environment.

In short, by observing the three basic rules, designers can increase their chances of success because they focus attention on, and help to combine, functional efficiency, economy and safety. Without this combination no satisfactory solution is likely to emerge.

Table 7.3: Checklist for Embodiment Design (Pahl and Beitz, 1996)

Headings	Examples
Function	Is the stipulated function fulfilled? What auxiliary functions are needed?
Working Principle	Do the chosen working principles produce the desired effects and advantages? What disturbing factors may be expected?
Layout	Do the chosen overall layout, component shapes, materials and dimensions provide adequate durability (strength), permissible deformation (stiffness), adequate stability, freedom from resonance, unimpeded expansion, acceptable corrosion and wear with the stipulated service life and loads?
Safety	Have all the factors affecting the safety of the components, of the function, of the operation and of the environment been taken into account?
Ergonomics	Have the human-machine relationships been taken-into account? Have unnecessary human stress and injurious factors been avoided? Has attention been paid to aesthetics?
Production	Has there been a technological and economic analysis of the production processes?
Quality Control	Can the necessary checks be applied during and after production or at any required time, and have they been specified?
Assembly	Can all the internal and external assembly processes be performed simply and in the correct order?
Transport	Have the internal and external transport conditions and risks been examined and taken into account?
Operation	Have all the factors influencing the operation such as noise, vibration handling, etc been considered?
Recycling	Can the product be reused or recycled?
Maintenance	Can maintenance, inspection and overhaul be easily performed and checked?
Costs	Have the stipulated cost limits been observed?
Schedules	Can the delivery dates be met? Are there design modifications that might improve the delivery schedule?

7.4 Detail Design

At the detail design phase the embodiment of technical products are completed with final instructions about the layout, forms, dimensions and surface properties of all individual components, the definitive selection of materials and a final scrutiny of the production methods, operating procedures and costs. Another, and perhaps the most important, aspect of the detail design phase is the elaboration of production documents and especially of detailed component drawings, of assembly drawings and of appropriate parts lists.

Depending on the type of product and production schedule (one-off, small batch, mass production), the design department must also provide the production department with assembly instructions, transport documentation and quality control measures; and the user with the operating, maintenance and repair manuals. The documents drawn up at this stage are the basis for executing orders and for production scheduling, that is, for operations planning and control. In practice, the respective contributions of the design and production departments in this area may not be distinct.

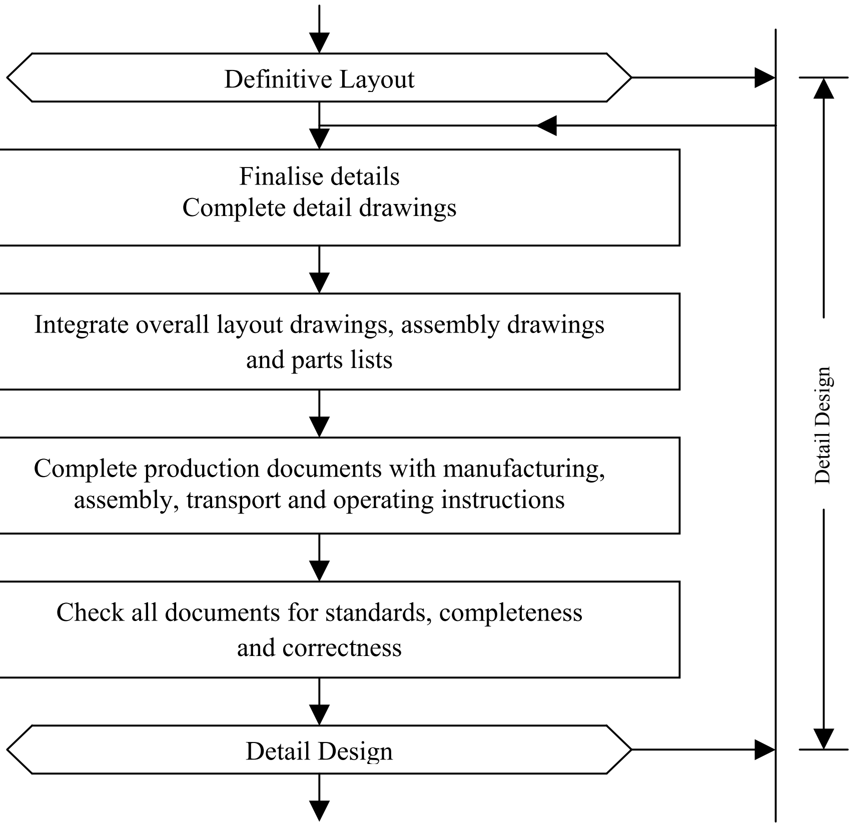


Figure 7.7: Steps of Detail Design (Pahl and Beitz, 1996)

The detail design phase involves the following steps (See Figure 7.7):

1. Finalising the definitive layout, comprising the detailed drawing of components, and the detailed optimisation of shapes, materials, surfaces, tolerances and fits. Optimisation aims at maximum utilisation of the most suitable materials, at cost effectiveness and at ease of production, due heed being paid to standards (including the use of standard parts and company repeat parts).
2. The integration of individual components into assemblies and through these into the overall product is carried out. This activity is strongly influenced by production scheduling, delivery dates, and assembly and transport considerations.
3. The completion of production documents with production, assembly, transport and operating instructions is another crucial aspect of the detail design phase.
4. Equally important is the checking of all documents and especially of detail drawings and parts lists for
    a. observance of general and in-house standards;
    b. accuracy of dimensions and tolerances;
    c. other essential production data; and
    d. ease of acquisition, for instance, the availability of standard parts.

Whether such checks are made by the design department itself or by a separate standards department will depend largely on the organisational structure of the company concerned, and plays a subordinate role in the actual execution of the task.

Detail design is very domain and product dependent and designers should refer to many technical handbooks, suppliers' catalogues and standards that deal with the detail design and selection of machine elements. Detail design has a major influence on the production costs and production quality – and hence the success of a product in the market.

8. PROPOSED DESIGN METHODOLOGY

After making it clear that mechatronic products and processes have many superiorities over the conventional ones, it is not difficult to imagine that mechatronics is going to gain a greater place in our lives in the future. At this point however, there arise some questions about how to create actual mechatronics such as: “What kind of a development team could best design mechatronics? What should the organizational structure look like? How should the responsibilities be shared? Is any change needed in the engineering design methodology in order to create mechatronics? etc”.

In the following chapters, I will try to give reasonable answers to above questions. First of all, it is very important to determine the characteristics of the development team because as we have evaluated in Chapter 5: “Change of Design Methodology”, the organisational structure of the design team, coordination between the team members and order of the design activities of each discipline strictly affect the characteristics of the designed product. Thus, we have to first decide on who could best create mechatronics. Secondly, in order to eliminate the interior bureaucracy, increase the collaboration, distribute the responsibilities and make the design process as smooth as possible for the design team, a suitable organisational structure must be established. Therefore, I will propose a new structuring for product development department and will try to appoint proper responsibilities to each member of the team. Also, I will try to propose that this new structuring may create a new challenge to the organisation in technology pursuit. Finally, I will try to propose some adjustments at the conceptual design phase. Although, Craig, associate professor of mechanical engineering at Rensselaer Polytechnic Institute in Troy, N.Y., proposes that “Mechatronics does not change the design process” (quoted in Ashley, 2003), I will try to slightly change the conceptual phase of engineering design methodology and adjust it in order to better create mechatronics.

8.1 Superiority of the Use of Mechatronics Engineers in Design

In order to implement successful mechatronics, at least a successful implementation of concurrent engineering is needed. And successful implementation of concurrent engineering is possible by coordinating adequate exchange of information and dealing with organisational barriers to cross-functional cooperation (Shetty and Kolk, 1997). However, as it is going to be explained below, there are some difficulties at the implementation of concurrent engineering methodology while even it is not enough to create actual mechatronics.

- As their nature require mechatronic products and processes include large doses of mechanical, electrical, control and software engineering applications at the same scenery. However, getting these different disciplines to work together isn't always easy. Most manufacturing firms have their separate mechanical, electrical, and even control and software departments, each with their own managements, practices, and design tools. In order to implement successful mechatronics, these largely autonomous departments must be divided into smaller multi-disciplined teams focused on the end product. Unfortunately, not everyone is eager to give up their *long-held organizational power base* (Tomkinson, 1992). So the first obstacle to implement actual mechatronics through concurrent engineering immediately occurs at the beginning when the design team is being established.
- While mechanical, electrical, control and software engineers work together, they will not necessarily know or appreciate each other's constraints, priorities, strengths, and weaknesses. Such disconnects between the engineers of different disciplines can cripple the process of getting products to market in an effective and efficient manner. Thus, even in the concurrent engineering activities, in many cases the products come out to show functional excellence and sub-optimizations. These sub-optimizations increases as the products get more and more complex (Tomkinson and Horne, 1995). Therefore, in order to get rid of these disconnects, there is a need in the design team for somebody who knows the constraints, priorities, strengths and weaknesses of each disciplines.
- Even though a great percentage of today's design teams adopts to concurrent engineering methodology instead of sequential engineering methodology, communication and so collaboration are great problems especially at complex

projects in which applications of all different disciplines take place together. Due to the influence of concurrent engineering, traditional barriers between design and manufacturing have decreased; however *the lack of common interface language* has maid the information exchange in concurrent engineering difficult (Shetty and Kolk, 1997). For that reason, even though all the engineering activities starts concurrently, as the time goes on, each group concentrates on their own area instead of the whole design and so the design activity does not end with a synergistic synthesis of all disciplines. Therefore, in order to create an interface between all these disciplines, there is a need in the design team for somebody who knows at least a little bit of everything of the jargons of each discipline and who creates a bound between these disciplines.

- Conflict is normal and a basic problem when a team of people from different backgrounds come together. It is also bound to happen when the team includes highly skilled members who take pride in their contributions (Tomkinson and Horne, 1995). Actually, conflict is acceptable to some limits if the members of the team have great negotiation skills. However, negotiation is even difficult between diverse engineering backgrounds who do not necessarily understand other disciplines. Thus, conflict can be destroying even in concurrent engineering and cause sub-optimizations because an engineering design is a series of trade-offs and whoever makes the best trade-offs would have the best design, however, the conflict between different disciplines and the pride of some members prevent making the best trade-offs. Therefore, in order to win the conflict, there is a need in the design team for somebody who would get over conflict through negotiations and make the best trade-offs without being impressed by the pride of their background.

Considering all above problems related with the creation of successful mechatronics through concurrent engineering methodology, which is considered as the basic methodology for the implementation of mechatronics, I make my first proposal as:

Proposal 1: In order to create actual mechatronics, the design team must be fully structured by or at least must include some “mechatronics engineers”.

These mechatronics engineers must be multi-disciplined engineers who would know the constraints, priorities, strengths and weaknesses of all related engineering disciplines; who would know at least a little bit of everything of the jargons of these disciplines as well as marketing, sales, finance and other related groups and so create a bound between them by establishing a common interface language; and who would get over conflict through negotiations and make the best trade-offs without being impressed by the pride of their background.

There is an inclination that all the engineering disciplines and so their knowledge is going to merge and create a complete integration in one multi-disciplined engineering field. It is easy to see such kind of an inclination through the change of design methodologies. Different engineering disciplines were completely separated at the beginning of the history of design methodologies. In early stages of craft engineering methodology, the design of completely single disciplinary mechanical products (the only discipline which has been in practice) was even made by separate designers who would not ever communicate with each other. At this primary design stage, there were not any relation between the separate part's designers and so the end products were completely single disciplinary and they could not show any kind of synergy. In the following years, at the beginning of mass production, these separate part designers were brought together in order to create some synergy between them. Later on, some electrical applications started to be added to the main mechanical product afterwards. Thus, some primary multi-disciplinary products started to occur (See Figure 8.1).

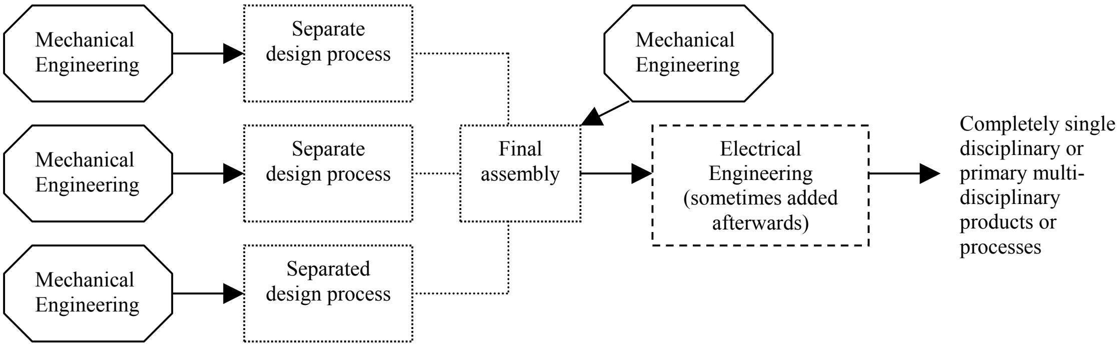


Figure 8.1: Craft Engineering Methodology

Through the mass production age, parallel to the technological developments, products started to include more and more electrical, control and software applications. The new design approach, sequential engineering design methodology

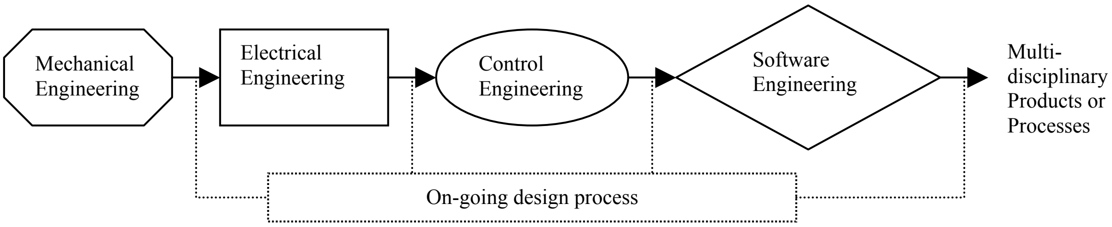


Figure 8.2: Sequential Engineering Methodology

has replaced craft engineering applications (See Figure 8.2). At this period, engineers of different disciplines added their own applications sequentially onto the product one after the other. Therefore, the final products were multi-disciplinary (initial electro-mechanical components). There was synergy within each engineering field but not between the disciplines.

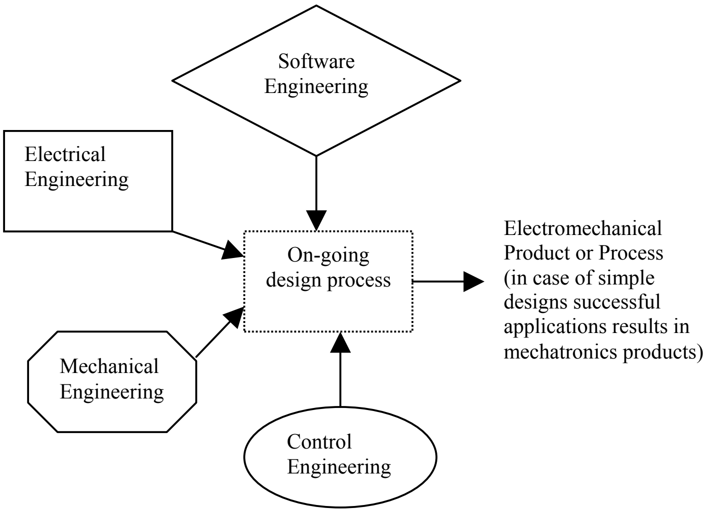


Figure 8.3: Concurrent Engineering Methodology

Increasing doses of electrical, control and software applications in the products and processes have brought together the need for synergistic blends. That was because many of the multi-disciplinary products showed only functional excellences and the end products were suboptimal. The initial solution of engineers to this problem has been concurrent engineering methodology (See Figure 8.3). As expected, when the different engineering groups have been combined in the same group, that is when they started their design activities at the same time and joined the whole design activity from the beginning to the end, the result was much more synergistic and the end products were

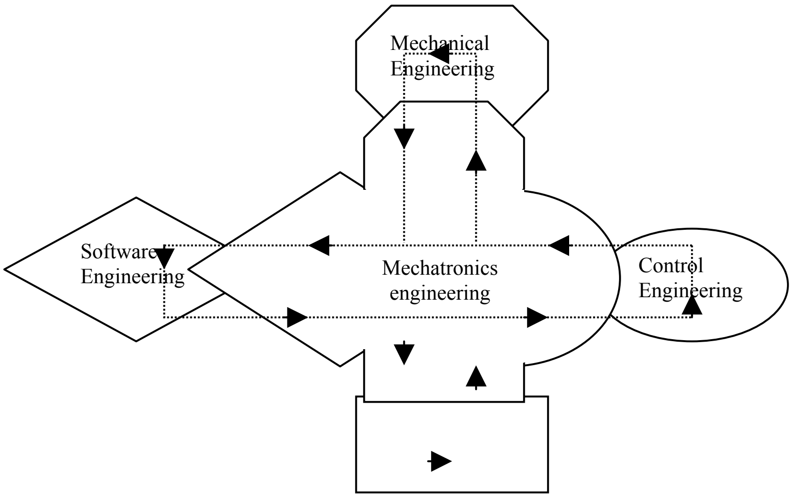


Figure 8.4: Combined Engineering Methodology

something more than simply electro-mechanical products but they were mechatronic products. However, as it is explained above there still are some lacking points and so some problems at this methodology. Somewhat a further combination is needed. This further combination is the combination of the knowledge of different engineering disciplines in one engineer who is called as **mechatronics engineer**. As I propose above when these new engineers used efficiently in the design teams, the end products will be much more likely to be mechatronics products. Under the following heading, I will propose a new design methodology for this new structure, which I call "combined engineering methodology" (See Figure 8.4).

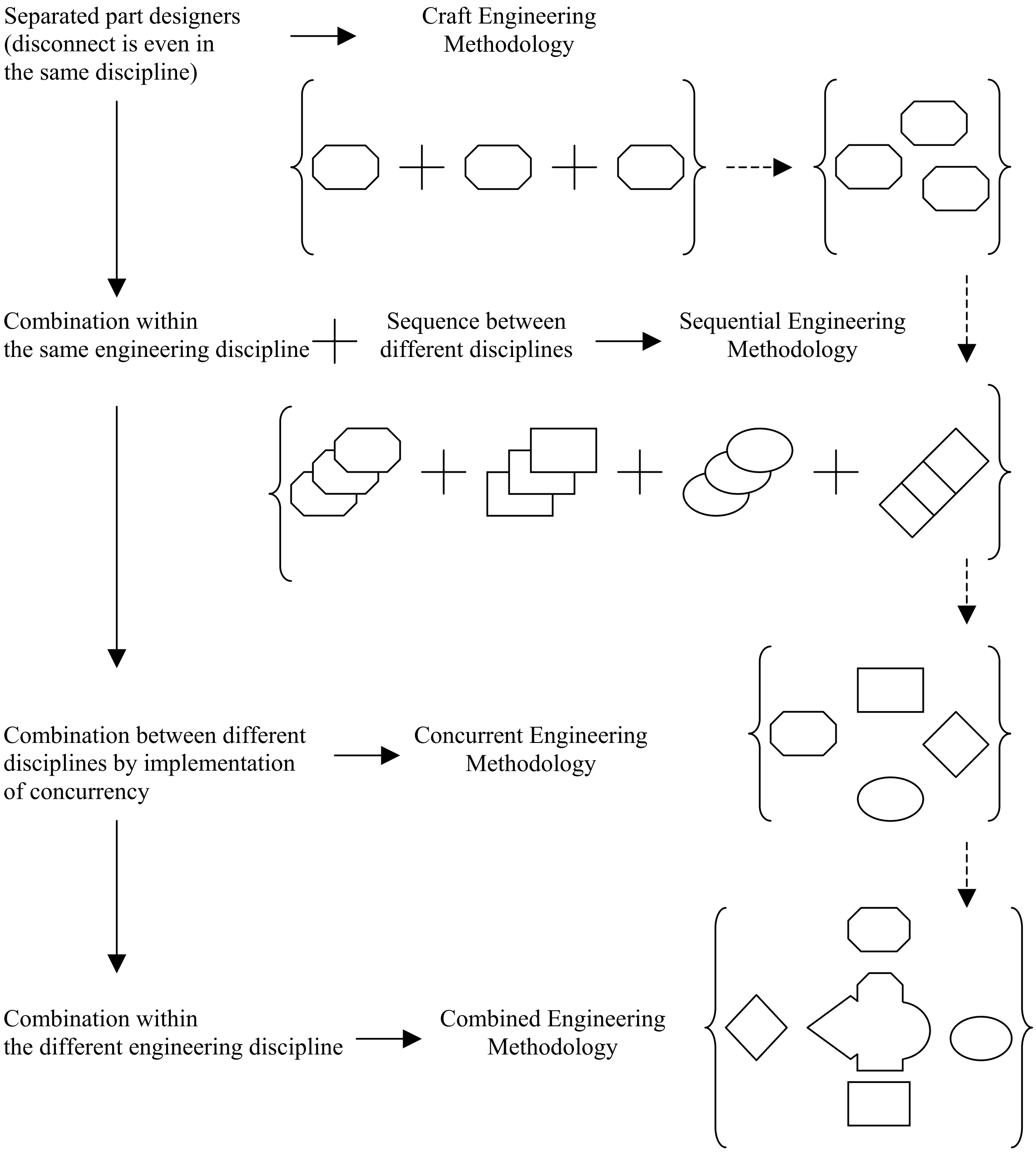


Figure 8.5: Change of the design methodology

Figure 8.5 summarizes above explained inclination for combination in the design methodology.

8.2 New Structuring of Product Development Department

8.2.1 Place of Mechatronics Engineers in the Engineering Design Methodology

After making it clear that for the creation of actual mechatronics use of mechatronics engineers are necessary, we need to define at which point of engineering design methodology they will enter the design process and how the organisational structure should be. The answers to these questions are hidden within the explanations of activities of each phase of engineering design methodology. In the former chapter, I have explained what the entrance of mechatronics engineers add to the design process. First of all, they will provide a common interface language between different disciplines. Thus, they should take place where the different disciplines come together and tries to communicate with each other. Secondly, they will get over conflict through negotiations and make the best trade-offs without being impressed by the pride of their background. And finally, they will know the constraints, priorities, strengths and weaknesses of all related engineering disciplines which could help while making trade-offs and selecting solution alternatives. Thus, they should take place where the most trade-offs are made and solution alternatives are selected. If we evaluate the steps of engineering design methodology (see Chapter 7), we detect that such activities are mostly carried out at “Clarification of the Task” and “Conceptual Design” phases of the methodology. Also, after making main trade-offs, there is an obvious need for someone who would provide a common interface language in order to keep the coordination alive between the design works of different disciplines and secure the precedence of end-product-focus till the end of the whole design activity through the “Embodiment Design” phase. Therefore, it is easy to say that we need to employ mechatronics engineers mainly at these phases. However, as I will explain here and widely in the following chapter, they may play an important role at the “Product Planning” phase as *technology pursuit team* as well.

Figure 8.6 tries to exhibit how MEs should be situated through the steps of engineering design methodology. The value created and added to the design process by mechatronics engineers starts just at the beginning of design methodology, namely at “Product Planning” phase. At the product planning phase of the engineering design

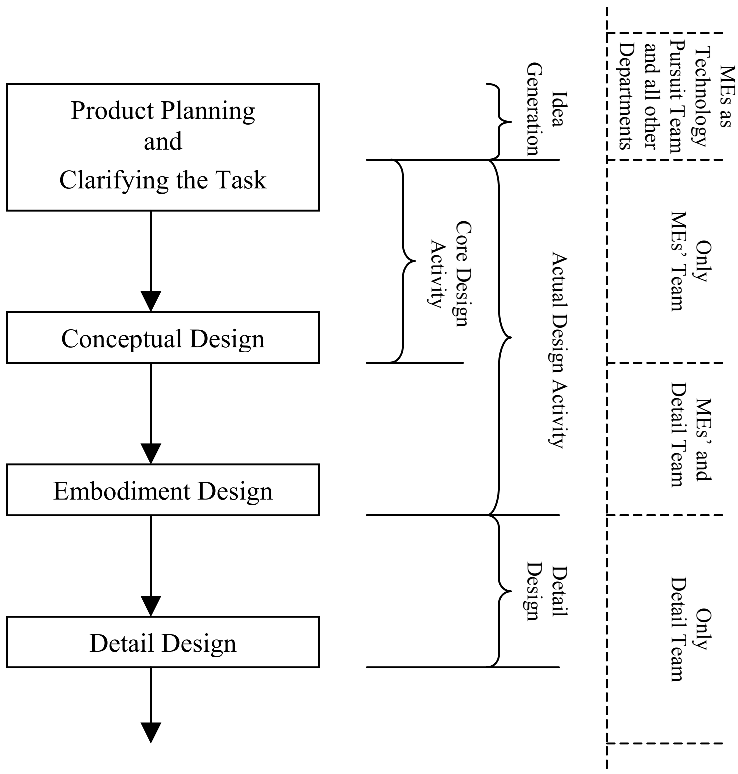


Figure 8.6: Place of MEs in the Engineering Design Methodology

methodology, the basic idea for a product or a process is generated and specified. For such an activity, analysis of current situation, determination of the status of technology, estimation of future developments, and identification of strategic opportunities have crucial importance; which are mainly the responsibilities of chief technology officer and his/her technology pursuit team. In the following chapter I will propose that a team of mechatronics engineers may be a challenge for a company because such a team would better make technology pursuit compared with a team of single disciplinary members. Therefore, if MEs are employed in design, they would play two different roles at product planning phase. In the first role, they play as ordinary team members of the product planning group which also includes marketing, sales, R&D, finance and manufacturing specialists. In this role, they have an equal decision power as the other team members and there is no precedence between any of the contributing disciplines. This product planning group, when they come together, assesses all the information created by individual disciplines such as marketing research results of the marketing team or future technology trend expectations of technology pursuit team, generates product ideas, evaluates and selects these ideas, and finally approves new product ideas and prepares new product proposals. The second role of MEs at this step is to act as the technology pursuit team and carry out the works which are the responsibilities of chief technology officer and his/her team such as determining the status of technology, estimating future developments, and identifying strategic opportunities. Finally they report their findings to the product planning team.

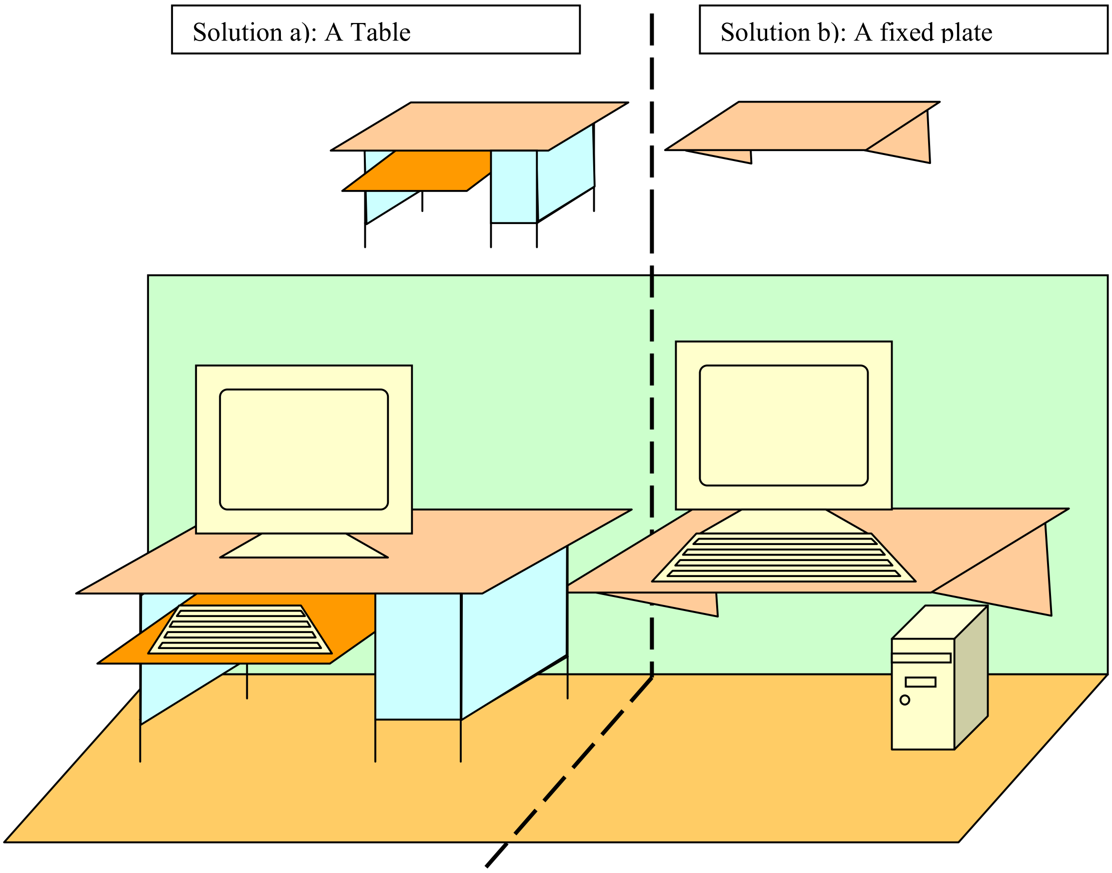


Figure 8.7: Different solutions for the same product proposal

The second step of preparation for design, namely clarification of the task phase, starts after a product proposal is made through product planning phase. Together with this step main contribution of MEs to design process begins. Even though a product proposal is created at the product planning phase and a preliminary requirement list is prepared, all the requirements, wishes and demands must be evaluated by the point of view of designers. That is because some fixed solution ideas or concrete indications which are implicit in the task formulation may have already created an adverse effect on the final outcome by giving an implicit direction to the designer for the end product. Figure 8.7 demonstrates two different solutions for the same product proposal. The initial product proposal is: "The client needs a table in order to put his/her computer on it and work. So, we need to find a solution to that need". If a design team starts with this preliminary product proposal and if they do not clarify the actual design task, the end product will be a table in any case because they have received an implicit direction by this product proposal. The preliminary proposal starts with the words that "the client needs a table", so the end product comes out to be a kind of table. However, a simple fixed plate may be a great solution for the needs of the client in some cases. The design team with an initial direction to design a table can not create such a solution if they do not clarify the task by a solution oriented point of view. Therefore, being in contact with the client and questioning the situation, the preliminary product proposal should be clarified as "The client needs something in order to put his/her computer on it and work, under some specified conditions (These conditions are the requirements such as some dimensional restrictions, some information about the place of the end product, some wishes etc)".

The same problem stated above may occur between the solution proposals of different engineering disciplines. When the design team receives a product proposal from the product planning team, they may have already received some fixed solution ideas or concrete indications which are implicit in the task formulation as well. For example some common solution alternatives may have already been created in the minds of members of each discipline who enters the product planning phase and these ideas may be included in the proposal, which causes sub-optimizations at the end-product. In order to prevent such initial sub-optimizations, there is an obvious need for such a clarification that would eliminate such inherently created fixed solution ideas. However, it may be very difficult for single disciplinary engineers to carry out a successful clarification without being affected by their backgrounds in complex designs. That is because, even at these initial stages of the design, they inherently try to find imaginary solutions to the problems in their own area of knowledge. Therefore, they bump into some fixed solutions and try to shape the final requirement list for making it easy to carry out these fixed solutions at the end. Another problem happens to occur when eliminating restricting requirements at this stage. It is because they do not necessarily know the constraints, strengths and weaknesses of each other, they resist to the elimination of the constraints which are related with their own area. And so some conflicting points occur immediately.

Consequently, when clarifying the task, there is an obvious need for someone who would not bump into fixed solutions by being affected by his/her background and who would easily make the necessary eliminations of the restricting constraints without falling into conflict. Therefore, mechatronics engineers must be situated at the clarification of the task phase.

After the clarification of the task, the concept of the product/process is generated through the conceptual design phase. Together with the clarification of the task phase, conceptual design phase may be called as "Core Design Activity" because through these phases the main design problem is developed and the main structure of the product/process is created. Similar to the clarification of the task phase, MEs are needed in conceptual design phase for their specifications such as being able to make decisions without being affected by a single disciplinary background, preventing insufficient conflict, and making best trade-offs.

Through the conceptual design phase, the overall function is divided into sub-functions and the function structure of the end product/process is developed, alternative solutions for these sub-functions are found, these alternatives are evaluated and selected through some trade-offs, and finally they are combined and principle solutions are obtained. In case of multidisciplinary – in this case mechatronic - products/processes, at each of these activities a number of people from different backgrounds must work together and make the necessary selections through some trade-offs together, which is a very difficult process because of the conflict that inherently occurs between people of different backgrounds. While trying to find solutions to each sub-function, every discipline tries to find solutions that are related with their own background and while combining these sub-functions in order to create overall solution variants, they try to put precedence to their own solutions. While making trade-offs each group is strictly affected by the proud of their background and so a conflict which may sometimes be impossible to win comes out to interrupt making the best trade-offs and selecting the most suitable combinations. Another problem is the loss of end-product focus. It is because different disciplines do not know the constraints, priorities, strengths and weaknesses of each other, while finding solution alternatives to each of the sub-functions they try to find the best solution to the sub-function which is related with their background without considering how it would affect the work of other disciplines and so the overall function. Even if all the proposed sub-function alternatives were perfect by themselves, they may not create a perfect end-product if these interdisciplinary affects are not considered. Therefore, in order to keep the end product focus alive, a good communication between each discipline and a well understanding of the constraints, priorities, strengths and weaknesses of each other is essential. Of course, a common interface language is crucial for such a successful coordination.

Eventually, while carrying out the conceptual design of the product/process, there is an obvious need for someone who would know the constraints, priorities, strengths and weaknesses of each discipline and therefore would easily decide which function would be better carried out by the application of which discipline, who would have the ability to understand and evaluate the possible effects of the applications of each discipline over the others, who would better make the best tradeoffs while selecting the solution alternatives of each sub-functions without being affected by the proud of his/her background, and who would select the best combinations while creating solution variants by his/her ability to asses the interdisciplinary affects and create an end product focus. Therefore, considering their abilities it is easy to say that mechatronics engineers must be mainly situated at the conceptual design phase of the engineering design methodology.

After the concept of the design is developed, the product/process starts to come to the life and receive its initial shape through the embodiment design. While it was only an idea on the papers after the conceptual design, it starts to be created physically through the embodiment design phase and it receives its initial face after this embodiment. Throughout the embodiment design phase scale drawings and preliminary layouts for main and auxiliary function carriers are developed, interconnections between sub-functions are determined and shaped, form designs are created, overall layouts are evaluated against technical and economic criteria, preliminary production documents are prepared, and after optimisation and checking for errors and disturbing factors embodiment is finished by a definitive layout. In order to make a successful embodiment for the creation of an actual mechatronic product/process keeping the end product focus alive, creating an appreciable synergy between all included disciplines, and developing a complete synergistic integration of the whole work done have crucial importance. The most common problem that is faced by the design team while trying to do this is the lack of common interface language between different disciplines. Even if they were able to develop the concept of the product/process together successfully, members of each discipline turn back to work separately in their own area and interdisciplinary effects between these different disciplines are omitted because they cannot communicate successfully with each other as the things start to be detailed. However, many important constraints which happen to occur within the work of one discipline and may affect the work of the others are created during the embodiment design and if they are omitted because of the lack of coordination, these omitted constraints weaken the synergy and cause the sub-optimisations. Being able to understand the constraints, priorities, strengths and weaknesses of other related parties and being able to assess the possible effects of the work done by one discipline over the others are the other critical success factors for the creation of mechatronics. However, in order to be able to do them, members of each discipline have to know an appreciable amount of the constraints, priorities, strengths and weaknesses of other disciplines, which is almost impossible for single disciplinary engineers. Therefore, there is an obvious need for some people who would create a common interface language between different disciplines and create coordination; who would know the constraints, priorities, strengths and weaknesses of each discipline and would be able to assess the possible affects of the work of each discipline over the others; and who would keep the end product focus alive by being able to keep command of the whole design through a tight coordination and well understanding of the work of others. Eventually, considering their abilities it is not difficult to say that mechatronics engineers must be widely situated at the embodiment design phase of the engineering design methodology, too.

The final step of engineering design methodology is detail design phase. As its name implies, throughout this phase, all the works that are created through former phases are detailed. Detail drawings of each part, overall layouts and assemblies are created; part lists and production documents are developed; transport and operating instructions are completed; and after an overall checking for standards, completeness and correctness the whole activity is completed. All these detailing activities are related with final retouching of each single discipline and there is not an extensive need for a multidisciplinary point of view at this phase. Therefore mechatronics engineers may or may not be included at this phase of design methodology because they are not necessarily expected to have very much detailed information of any of the disciplines. If they are included at the detail design phase, that may be for overall reviewing.

Consequently, if we separate the design methodology from the initial preparations for product planning, mechatronics engineers are expected to be situated in “clarification of the task phase”, “conceptual design phase”, and “embodiment design phase”. It may be better to only employ mechatronics engineers in the clarification of the task and conceptual design phases because main tradeoffs and selections are made through these phases and there is a great need for an overall multidisciplinary perspective at these phases and as I have explained all of these activities may be better carried out by mechatronics engineers. However, single disciplinary members of the design team may enter the activities whenever needed. If the core design team (team of MEs) needs to receive the point of view of any member of detail teams (single disciplinary members of design team), these single disciplinary members may join the activities. Nevertheless, it would be better if the core design team makes the tradeoffs and selections by themselves. In the embodiment design phase however, the need is obvious for both of multidisciplinary and single disciplinary members at the same time. Therefore, mechatronics engineers must be situated together with single disciplinary members throughout the embodiment design phase. Finally, as it is explained above, detail design phase is mainly the task of single disciplinary members and mechatronics engineers may or may not be included at this phase.

Therefore, I make my second proposal as:

Proposal 2: Mechatronics engineers must be mainly situated in "clarification of the task phase", "conceptual design phase", and "embodiment design phase" of engineering design methodology. Omitting the fact here that they may be the technology pursuit team of the organisation, they are not expected to play any important role either at "product planning phase" or at "detail design phase".

All above explanations make an implicit explanation about the organizational structure of the design team as well. Mechatronics engineers will have an overview of the activities of each engineering discipline throughout the whole design activity; they will provide a common interface language and therefore will provide coordination between different disciplines; they will keep the end-product focus alive and therefore will put pressure over the single disciplinary members; and they will have the power to make all the tradeoffs and selections. Therefore, all these appointed missions implicitly propose that mechatronics engineers should at least be the team leaders of the single disciplinary members. At this point, we need to add one more capability to mechatronics engineers that they should also have managerial skills. That is, their education should also include management training to some level as well.

Figure 8.8 tries to exhibit how the structure of design team should be when mechatronics engineers enter the engineering design methodology for the creation of actual mechatronics. This structure is so suitable in order to carry out what is appointed for mechatronics engineers. The core design team, namely the team of mechatronics engineers, will start the design activity and create the concept of the design by a multidisciplinary perspective. However, some detailed design activities which are very special to single disciplinary engineering fields must still be carried out and these activities may be better carried out by highly qualified specialists of single disciplinary engineering fields. Nevertheless, some kind of overview and leadership of mechatronics engineers are needed in any case. Therefore, there must be a team of mechatronics engineers that each member of whose will be responsible for the activities of one of the engineering fields. They will lead to the single disciplinary detail teams. These detail teams will work together with their leaders and with the mediation of their leader with the members of other disciplines throughout the embodiment design phase. Later on, they will polish the design of their own work area during the detail design phase. Some mechatronics engineers may also be situated in these detail teams depending on the complexity of the designed product/process in order to help the team leader at their pre-appointed tasks.

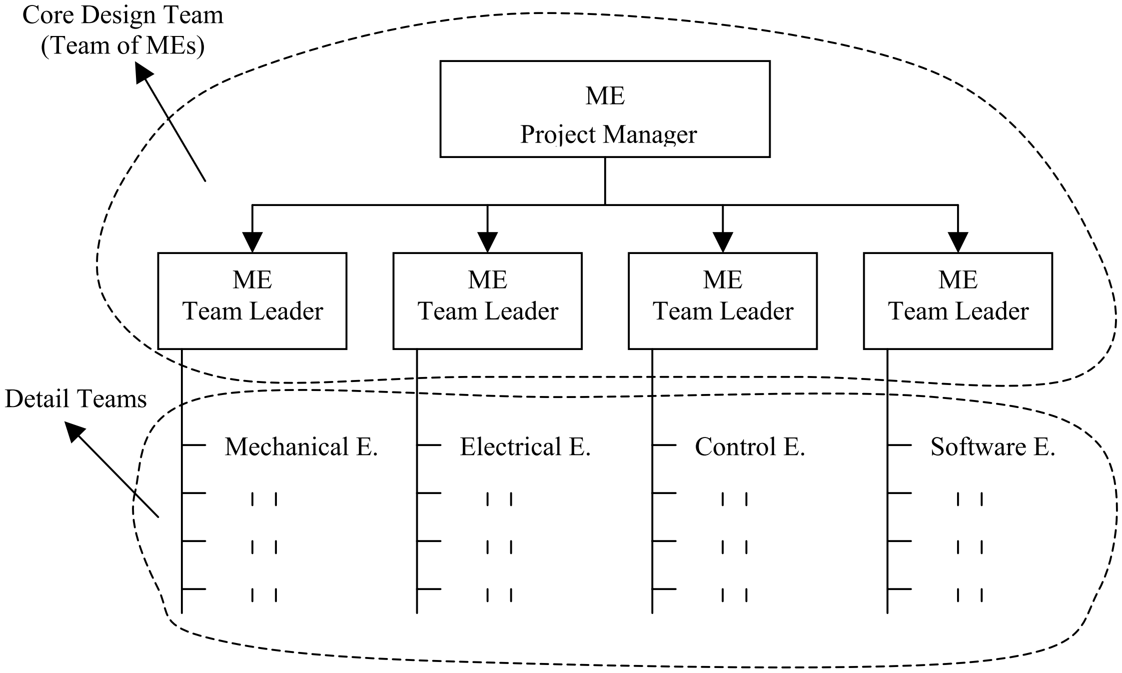


Figure 8.8: Structure of Mechatronic Design Team

After creating such a structure for design team, there comes out another issue about how to place that design team(s) within the whole organizational structure. As I have mentioned before, at least a concurrent engineering application is needed for the creation of mechatronics and in order to create a concurrent engineering application the organisational structure must allow the different engineering groups come together and work apart from their own departments. That is, for creation of a concurrent engineering application, the organizational structure must at least be a matrix organization or a project organization (See Figure 8.9). Very similar to concurrent engineering structure, the structure of mechatronic design team requires at least a matrix organisation because different engineering groups are still needed to come together and work together. Figure 8.10 exhibits the organizational structure for combined engineering methodology (mechatronics design methodology) in a project organization and Figure 8.11 exhibits the same structure in matrix organizations. In case of project organisations and heavyweight project matrix organizations general managers are more likely to be mechatronics engineers because considering their

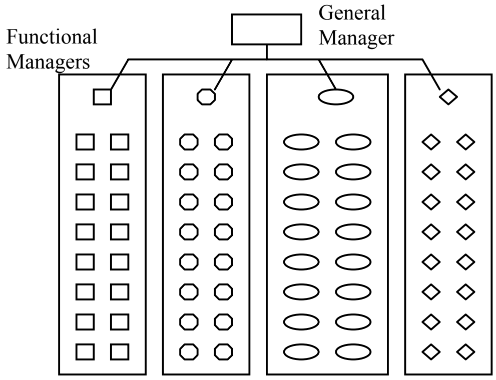


Figure: Functional Organisation

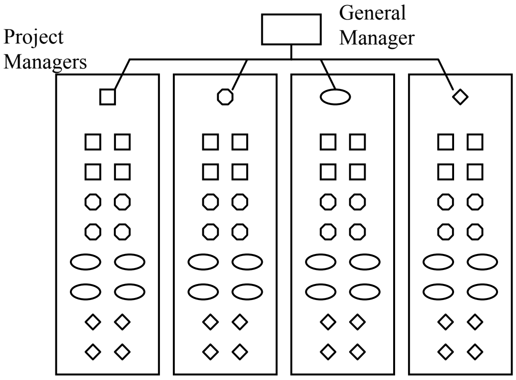
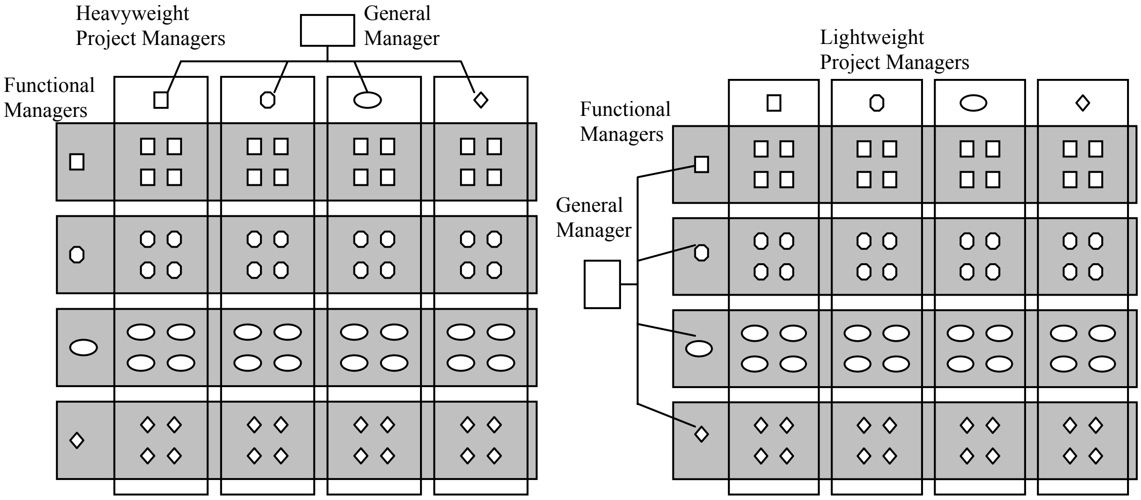


Figure: Project Organisation



a) b)

Figure 8.9: Matrix Organizations, a) Heavyweight Project Matrix Organisation, b) Lightweight Project Matrix Organisation

abilities and the responsibilities that are appointed to them would probably carry them to managerial positions.

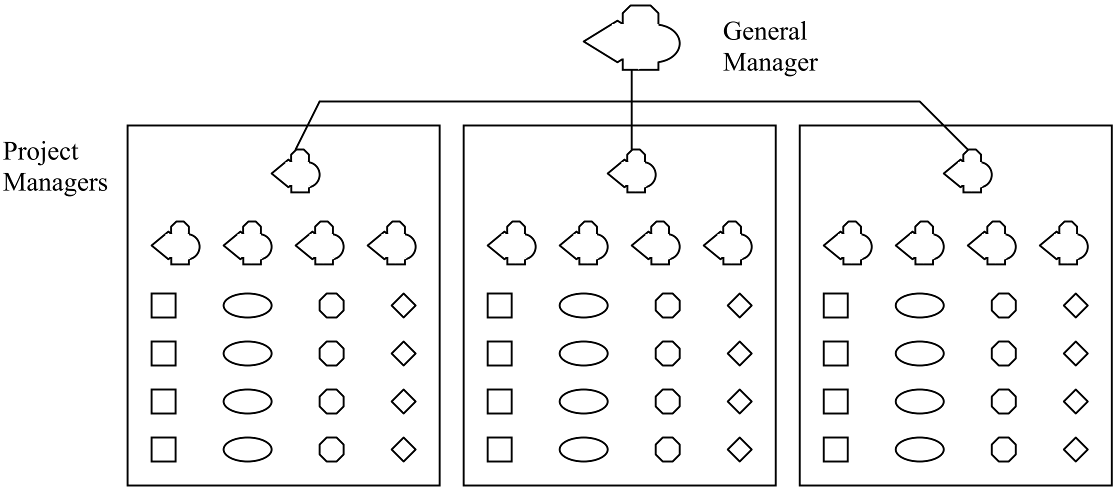
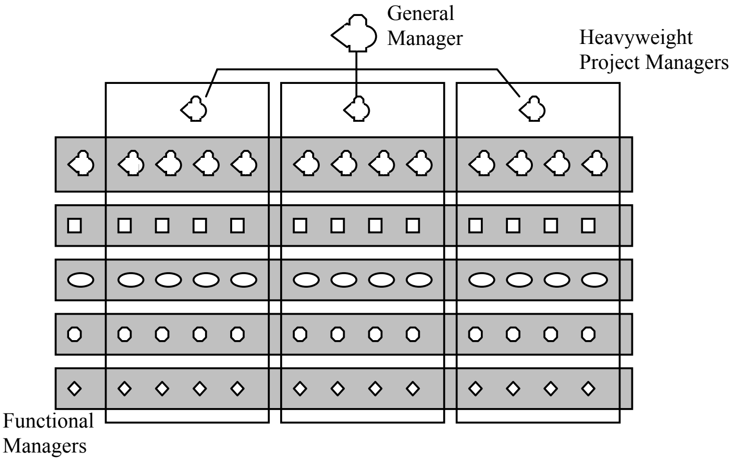
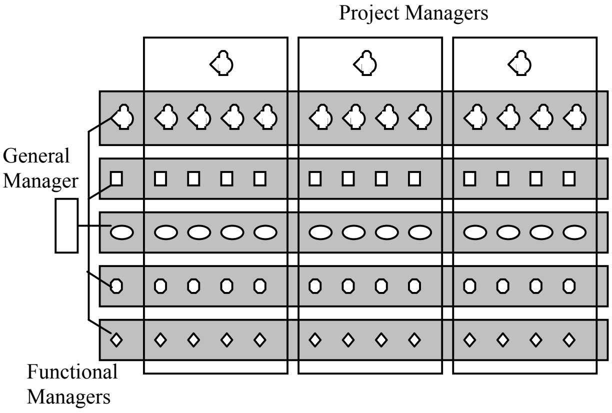


Figure 8.10: Organizational Structure for Combined Design Methodology



a)



b)

Figure 8.11: Matrix Organisations for Combined Engineering Methodology a) Heavyweight Project Matrix Organisation, b) Lightweight Project Matrix Organisation

Depending on above explanations I make my third proposal as:

Proposal 3: The structure of mechatronic design team must be at least a matrix organisation and a project organisation would make the best structure. In any case, mechatronics engineers are expected to be the team leaders of each engineering group.

8.2.2 What Makes Mechatronics Engineers a Good Chief Technology Officer (CTO)

The significant role of technology in strategic business decisions has created the need for executives who understand technology and recognize profitable applications to products, services, and processes. Many companies address this need through the appointment of a chief technology officer nowadays.

In the 1950s and 1960s, many large corporations established beautiful research laboratories at locations remote from their headquarters and manufacturing facilities. The goal was to collect brilliant scientists and allow them to study relevant topics in an environment unhindered by day-to-day business concerns. The director of the laboratory was often a corporate vice president who did not participate in decisions regarding corporate strategy and direction. Instead, his responsibilities were to attract the best scientists, explore new ideas, publish respected research papers, and generate technologies that might become new products. From these origins, the modern CTO position calls for a technologist or scientist who can translate technological capabilities into strategic business decisions.

Although the CTO position is far from being standardized and each company has unique requirements for its CTO and provides a unique organisational structure into which the person will fit, some of the more prominent responsibilities of a CTO are (Smith, 2003):

- monitoring new technologies and estimating future developments,
- determining technological strategies and affecting corporate strategy,
- determining the status of technology, selecting and overseeing research projects,
- providing technical assessments of potential mergers and acquisitions,
- explaining products and technology strategies to the trade media, and

- participating in government, academic, and industry groups

Some of above responsibilities require mainly technical abilities, some require mainly managerial abilities and some require both of them. Therefore, a good CTO must have managerial skills together with his/her technical abilities. However, a remarkable researcher occasionally finds the management side boring or distasteful because it is more of an art than a science, or because the person does not have the right set of skills at the appropriate level for management. Thus, the best researchers do not always make the best R&D leaders (Larson, 1996).

For monitoring new technologies, well understanding of technical issues in all fields of engineering has crucial importance. A good CTO and so his/her technology pursuit team must have a remarkable sense of feeling the threatening and challenging new technologies that are generating newly in one of the engineering fields and would probably play an important role in the market of the company in the future. These new technologies may generate and develop within single disciplinary and/or interdisciplinary areas or sometimes generate in one area and mainly affect and develop in another area. If we remember the extract of Bosch Co. about the innovative developments of recent years that "innovation occurs mainly at the interfaces of the knowledge fields", we may easily understand the importance of interdisciplinary affects of technology. A technology which emerges in an area of knowledge and affects another area(s) in the future may have fatal importance while it may open new challenges/markets to the company if explored on time as well. For example, technological developments in digital camera sector have dramatically affected the photo-film sector. Therefore, having general information in all engineering areas to some degree; knowing the strengths, weaknesses, and constraints of all of them and so being able to explore the emerging new technologies that could be a challenge or would threaten the company in the future is another critical success factor for CTOs.

Evaluating and selecting successful research projects is another important factor. A CTO with his/her technology pursuit team is expected to determine the technology strategy of the company, determine the status of the technology and so evaluate, select and oversee the success promising research projects. In order to carry out all these responsibilities successfully, a good CTO must be capable of making successful selections by making successful trade-offs with the help of his/her technical abilities and by making successful assessments through economic and managerial criteria.

For creating good relations with trade media, government, academic, and industry groups, a good CTO must have remarkable communication and negotiation skills just beside his/her managerial traits and appreciable technical knowledge-base.

Keeping all above responsibilities and characteristics of a good CTO in mind, here below I remind the responsibilities and characteristics of a mechatronics engineer that I have proposed in the former chapters: Mechatronics engineers must be multi-disciplined engineers who would know the constraints, priorities, strengths and weaknesses of all related engineering disciplines; who would know at least a little bit of everything of the jargons of these disciplines as well as marketing, sales, finance and other related groups and so create a bound between them by establishing a common interface language; who would get over conflict through negotiations and make the best trade-offs without being impressed by the pride of their background; and who would have managerial skills.

Surprisingly this definition of mechatronics engineers includes all crucial traits of a good CTO. Therefore I make my forth proposal as:

Proposal 4: Mechatronics engineers would become better CTOs than a single disciplinary specialist.

Therefore, I can also say that the core design team (team of MEs) could make technology pursuit better than a team of single disciplinary members. At this point however, I need to add that including some outstanding single disciplinary members can add remarkable value to the team because some technologies may require some core information of a single disciplinary area that a mechatronics engineer is not necessarily expected to always have.

8.3 Conceptual Design of Mechatronic Products and Processes

In the former chapters I have made some proposals about the inclusion of mechatronics engineers in design activity and place of them within the engineering design methodology. It is clear that mechatronics engineers may add a remarkable value to the engineering design methodology and they should be included mainly in product planning phase, core design phase and embodiment design phase of the methodology. However, there arises another question at this point such as "Should there be any change in the engineering design methodology of Pahl and Beitz or is that methodology enough for the creation of actual mechatronics?"

Here below I try to point out the important factors that have to be included in the engineering design methodology for the creation of actual mechatronics. Then I make reasonable explanations for these factors and propose the regarding findings at the end of each heading. Considering all the proposals and evaluating the methodology of Pahl and Beitz, I will propose my own methodology for conceptual design of mechatronic products/processes within this chapter. As a response to above question, I will explain in the following paragraphs that conceptual design phase of the methodology of Pahl and Beitz has to be enlarged by a few steps in order to make the creation of actual mechatronics possible and easy.

As I have explained before, core design activity is carried out through the clarification of the task and conceptual design phases of the engineering design methodology. Therefore, I will concentrate on core design phase (actually conceptual design phase only), and will try to build up a convenient conceptual design phase for mechatronics design methodology in this chapter.

Here below are the important factors for the creation of actual mechatronics:

- *creating the end product focus and keeping it alive*

  End-product focus (solution orientation) is a must in mechatronics design. End-product has to be efficient and end-product has to be optimal. That focus is an inherent obligation in mechatronics such that its definition says that mechatronics is a complete integration of different disciplines. A perfect sub-function may not be a perfect part of the whole if it is not designed with the end-product focus within the whole design activity. In order to create such a complete integration and eliminate sub-optimisations, end-product focus is a must then.

  On the other hand, in order to be able to keep the end product focus alive and prevent sub-optimisations, the whole system has to be a mechatronics system. That is, while designing a mechatronics system all the affecting upstream and downstream processes have to be considered and included in the design. Otherwise, the design that is tried to be mechatronics will have to be adapted to the other parts which are not designed with mechatronics methodology and so the design will lose its synergy and its completeness in itself.

For example, if we are trying to design a mechatronic intra-logistic system then all the sub-functions within this system and also other affecting environmental systems such as production also must support the mechatronics design of that intra-logistics system. For instance, if you are not able to follow up the production with a mechatronic manner then you can not design the feeding system of that intra-logistic system with a mechatronic manner. That is because not being a mechatronic system, the production system creates some restrictions that the intra-logistic system has to be adapted, and so the end-product (end-process in this case) can not be considered as a whole. Therefore, a complete and synergistic integration can not be obtained.

Therefore, I make my fifth proposal as:

Proposal 5: In order to be able to design actual mechatronics, the designed system must be considered as a whole and designers must adopt the end-product focus and keep it alive throughout the whole design activity.

- *breaking the initial inclinations and common solution ideas down, helping to create an overall view of the whole design and finding combined solutions, and making it easy to evaluate the possible effects and extra requirements between all sub-functions by defining the categories of the sub-functions and finding the solution ideas within these categories*

  As I have explained before, designers inherently try to find imaginary solutions to the problems even at the very early stages of the design process and so sometimes bump into some fixed solution ideas if there are well known, common solutions to similar problems. Such common solution ideas for some sub-functions may cause sub-optimisations in the whole design because being very suitable solutions by themselves such solutions may not be a perfect part of the whole and cause the design activity to fall below the complete and synergistic integration barrier. Therefore, there is an obvious need for such a method that would prevent the design team from bumping into such unsuitable inclinations and common solution ideas.

Through the “definition of mechatronics” and “elements of mechatronics” chapters I have tried to explain characteristics of all included disciplines. I have pointed out their strengths, weaknesses, constraints and application areas. In general, we can say that data processing and communication activities can be better carried out by software applications; control and coordination activities can be better carried out by control applications; and material movement, power transmission, housing and aesthetics can be better provided by mechanical applications (See Figure 8.12). On the other hand, electrical applications obviously take place in everywhere that electricity is consumed, stored, processed, or produced.

It is because control applications may include software applications inside in some applications, while determining the categories of sub-functions it may sometimes be difficult to distinguish the control and software applications. For example, numerically controlled (NC) machines include a remarkable software application in their control system. However, during the category determination step engineers must depend on the rule that “A software application creates information through some algorithms according to some given restrictions and initial values.” It is because there is not any kind of information creation in NC machines and because the machine only carries out pre-determined activities then the included software applications must b considered as a part of control system and must not be categorized as software application. CNC machines can be a good example at this point. By including some kind of computer applications, CNC machines differ from NC machines. The included computer application creates some information and tells the machine how to act by renewing the preset

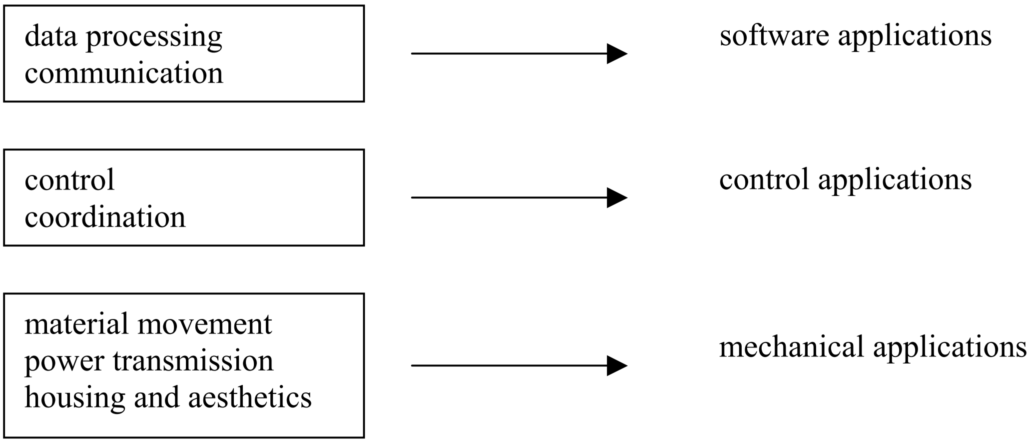


Figure 8.12: Criteria for determining the categories of sub-functions

values of the control system. Therefore, such applications in CNC machines can be categorized as software applications.

Ultimately, we can say that design team must try to find initial solution ideas for sub-functions regarding that common information. Such an inclination in solution finding efforts easily eliminates fixed solution ideas by forcing the designers for evaluating the basic categories of the sub-functions and then finding suitable solutions within these specified categories at first.

For example: If the design problem is the design of a brake mechanism for cars then designers can easily bump into a common solution and finalize the design by a pedal (for initiation of braking) + some rods (for power transmission) + a compression mechanism (for slowing the wheels). At this common solution, the mission of the rods is power transmission. However if we break the common inclination down and consider the main problem with a mechatronics view, we easily come up with a finding that the actual mission of these rods are information transfer (or let’s say communication). The rods transfer the information that “there is a need for braking” (which is created by the initiative movement of the pedal) from the pedal to the compression mechanism. Therefore, it is because communication activities can be better carried out by software and electrical applications, in a mechatronic solution there is no place for these rods.

Defining the categories of sub-functions not only eliminates fixed solution ideas but also helps evaluating the possible effects and extra requirements between all sub-functions and creating an overall view of the whole design and finding combined solutions.

It becomes easy to find relations between sub-functions when we define the category of sub-divisions because sub functions would probably affect each other through the same category of works that they include inside. For example, if there are mechanical, control and software applications in both of two sub-functions then these sub-functions affect each other through the same category of works. That is, mechanical applications of one sub-function affect mechanical applications of the other, control applications affect the control applications and software applications affect the software applications of the other. Therefore, defining the categories of sub-functions at the beginning makes it easy to define possible effects of each sub-function over the others and to find out any extra requirement that could occur due to these effects.

On the other hand, determining the categories also helps creating an overall view of the whole design and finding combined solutions. After all categories of sub-divisions are found, design team may create flow charts and combine these flow charts in order to have an overall view of the whole design. All possible effects, extra requirements and combined solutions can be evaluated with that occasion.

Therefore, depending on all these explanations above I make my sixth proposal as:

Proposal 6: While developing the concept of the design through the conceptual design phase, the categories of the sub-functions must be defined according to the general information that "data processing and communication activities can be better carried out by software applications; control and coordination activities can be better carried out by control applications; material movement, power transmission, housing and aesthetics can be better provided by mechanical applications; and electrical applications take place in everywhere that electricity is consumed, stored, processed, or produced" and solution ideas must be tried to be found within these categories first if possible.

If such an activity is successfully carried out then the initial inclinations and common solution ideas can be broken down; an overall view of the whole design can be obtained at an early stage and combined solutions can be found; and evaluation of the possible effects and extra requirements between sub-functions becomes easy.

- *evaluating the possible effects and extra requirements between all sub-functions (increasing the evaluated relations) in order to create a complete integration and synergy.*

  As I have explained above end-product focus is a must in mechatronics design. End-product has to be efficient and end-product has to be optimal. Therefore, the whole design activity has to be carried out in order to create the most efficient end-product and it should not mainly focus on sub-functions.

  As proposed by Pahl and Beitz, at the conceptual design phase of engineering design methodology, a design team is expected to divide the overall function into sub-functions till the possible smallest sub-division, find some working principles to each of these sub-functions separately and then combine them to build up an overall function. At Figure 8.13 a, b, c, and d sections try to exhibit this structure. Sections e and f exhibit all relations that could probably be considered by the design team if that methodology is applied. As we see at these two schemes, when we divide the overall function into sub-functions and find working principles to these functions separately, we may probably lose some extra relations that could possibly occur if we had evaluated all sub-functions together. Therefore possible effects and extra requirements of some sub-divisions that could probably occur during the design of these sub-divisions and affect the design of others are omitted. Thus, the overall function that is created with such omissions through such a conceptual design activity would probably include some sub-optimisations and these working principles for sub-functions, which may be perfect and very efficient by themselves, may not build up a perfect solution at the end.

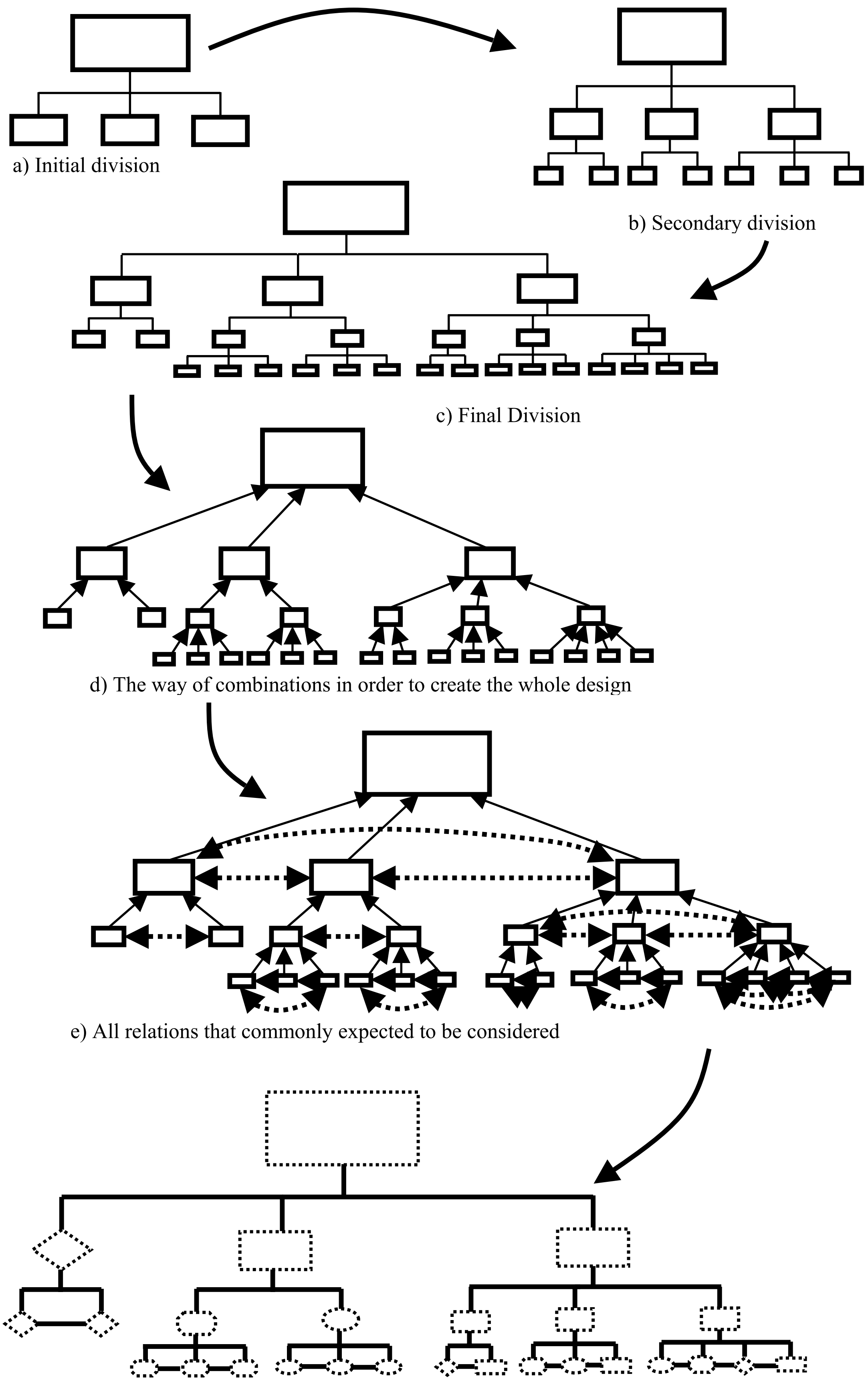
Depending on all these explanations I make my seventh proposal as:

Proposal 7: Conceptual design phase of engineering design methodology must direct the design team to evaluate all the possible effects and extra requirements between all sub-divisions (regardless of which sub-functions they belong) in order to create a complete integration and synergy.

I need to remind here again two important things. First of all, such an activity can be easily carried out if the categories of sub-functions are defined in advance and, secondly, sub-functions would probably affect each other through the same category of works that they include inside.

- *creating an overall view of the whole design and finding combined solutions at the beginning if possible:*

  Having an overall view of the whole design and finding combined solutions at the beginning have crucial importance in the creation of actual mechatronics. It is because what is important is the efficiency of end-product then the design methodology of mechatronics must include a way of providing the efficiency of the whole. In order to be able to do that design team must have an overall view of whole design, evaluate the upstream and downstream processes together, find out all affects of sub-functions over each other, determine any extra requirement that could come out through interrelations and finally try to find combined solutions for the whole design task.



a) Initial division

b) Secondary division

c) Final Division

d) The way of combinations in order to create the whole design

e) All relations that commonly expected to be considered

f) Another representation of all relations that commonly expected to be considered

Figure 8.13: Some schematic representations for conceptual design of engineering design

A real case study, which includes the design of two warships that are to be controlled by sophisticated digital systems and thus could be considered as a new type of a highly advanced mechatronics systems, that is examined by Rzevski may be a good example for this factor. According to the case study, the ships were designed and built but could not be made to work in time for delivery. The problem that had caused endless delays and overspending could be described in very simple terms: the performance of the three key constituent systems of the ship, namely the power system, communication system and weapon system, could not be synchronised for the warship to be able to fulfil its main function, that is, to execute the precision launching of missiles without interference from power and communication systems (Rzevski, 2003). This is clearly a conceptual design failure and the problem is obvious. The designers of the warships have probably divided the design activity to its sub-functions, developed them separately and then combined them to develop the whole. All the sub-tasks were perfect by themselves but they were unable to make a successful warship. The solution is again obvious and simple, they had to create an overall view of the whole design and find a combined solution for "successfully executing the precision launching of missiles without interference from power and communication systems". They should not focus on sub-functions and try to build up a successful power system, a successful communication system, and a successful weapon system.

Depending on all these explanations I make my eighth proposal as:

Proposal 8: For the design of actual mechatronics, design team must create an overall view of the whole design as early as possible in the design activity and find combined solutions at the beginning if possible.

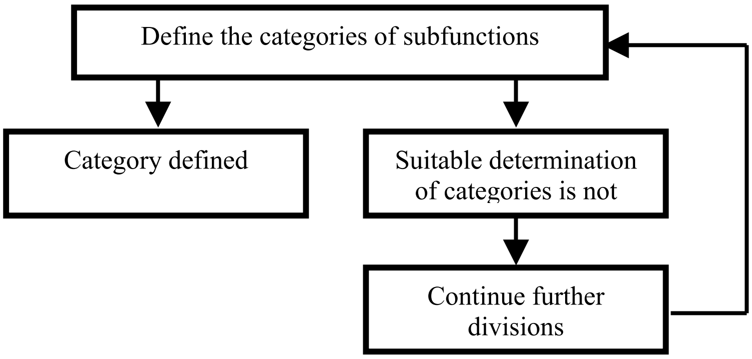
As I have explained before, for successfully doing that, after all categories of sub-divisions are found, design team may create flow charts and combine these flow charts in order to have an overall view of the whole design.

Considering all above proposals and explanations I have developed a new structure for conceptual design phase of engineering design methodology. Figure 8.14 exhibits that proposed conceptual design phase. The differences between this proposed conceptual design phase and the conceptual design phase of Pahl and Beitz starts from the step of "Establish function structures". Actually, the proposed design methodology does not change or eliminate the steps of the methodology of Pahl and

Beitz but adds some additional steps in order to provide creation of actual mechatronics.

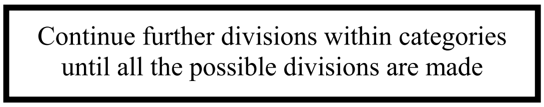
Here below are the additional steps:

- After establishing the function structure, following steps are proposed to be carried out in order to define categories of sub-functions. The categories of the sub-functions must be defined according to the general information that “data processing and communication activities can be better carried out by software applications; control and coordination activities can be better carried out by control applications; material movement, power transmission, housing and aesthetics can be better provided by mechanical applications; and electrical applications take place in everywhere that electricity is consumed, stored, processed, or produced”.

  If such an activity is successfully carried out then the initial inclinations and common solution ideas can be broken down; an overall view of the whole design can be obtained at an early stage and combined solutions can be found; and evaluation of the possible effects and extra requirements between sub-functions becomes easy.

- After first defining the categories of the sub-functions, further divisions must be made within the specified category. The sub-divisions of a sub-function must be within the same category with this sub-function if the category of sub-function is once defined. If there comes out some sub-divisions that are not within the same category of sub-function then there must be a problem in the primary determination of the category of the sub-function.

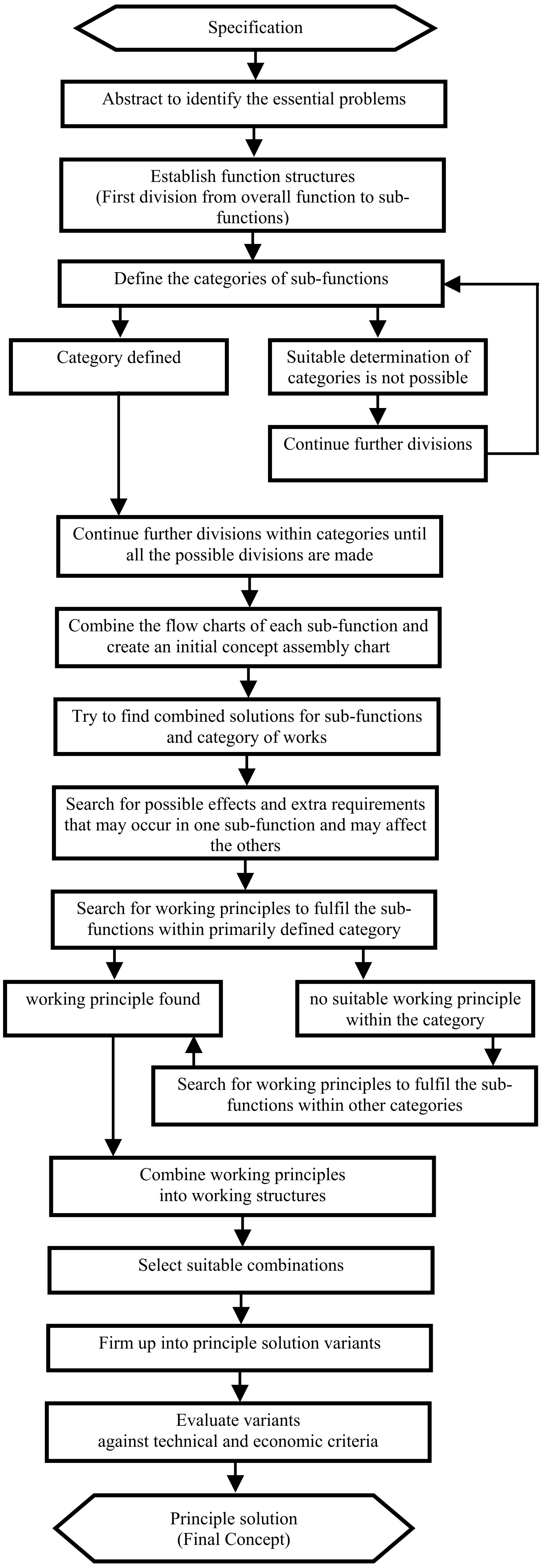


Figure 8.14: Proposed Conceptual Design Phase

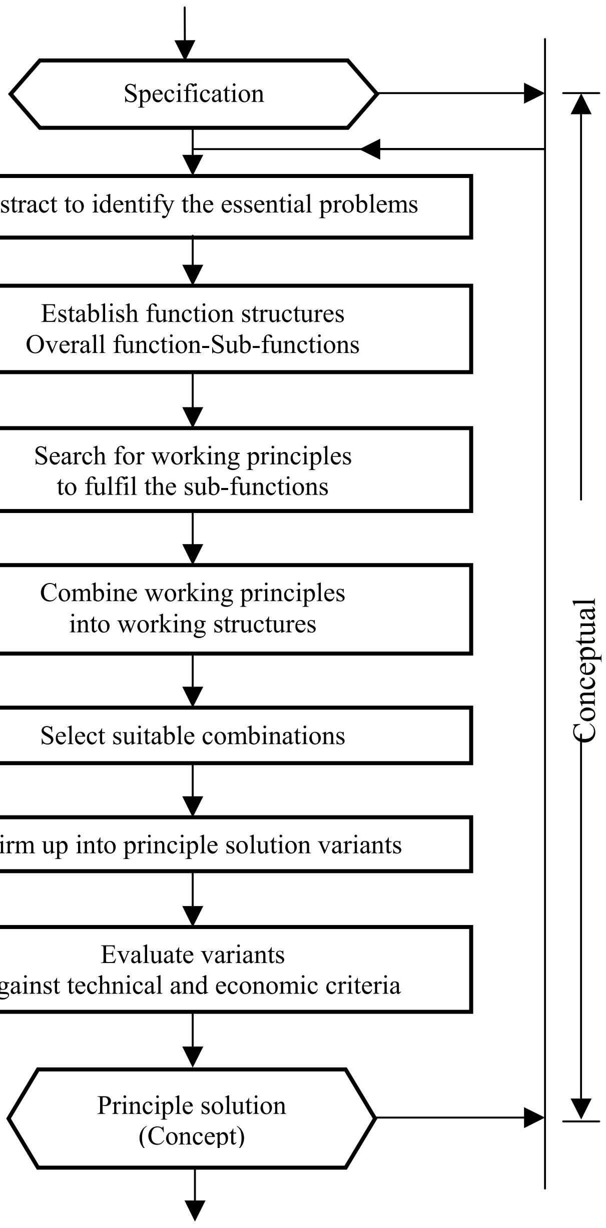
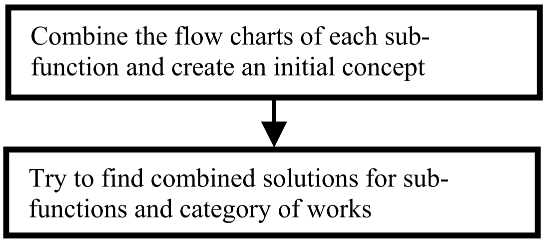
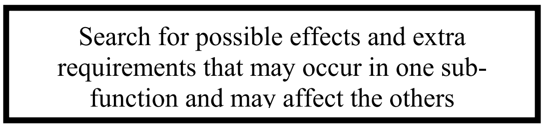


Figure 7.4 : Steps of Conceptual Design (Pahl and Beitz, 1996)

- After all the categories are determined, design team must combine the flow charts of each sub-function and create an initial concept. That step will allow the design team to create an overall view of the whole design and find combined solutions at such an early period of the design activity.



- Later on "Searching for possible effects and extra requirements" step comes.



- Finally, additional steps end with this group of steps at below. These steps force the designers to find solution ideas for sub-divisions and sub-functions within the primarily defined category. If a suitable solution is not found within the primarily defined category then another solution must be pursued in other categories.

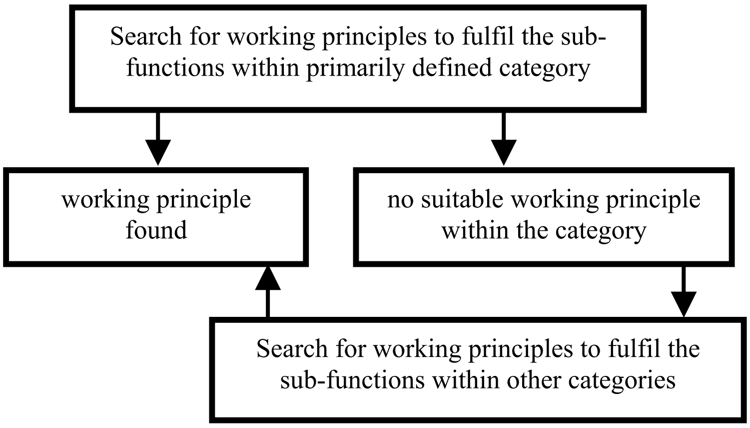


Figure 8.15 tries to exhibit some schematic representations for proposed conceptual design of engineering methodology. At sections a and b division of overall function into its sub-functions and categories of works represented. Section c represents the relations that commonly expected to be considered. Section d exhibits extra-relations that must be considered according to proposed engineering methodology for software applications and finally Section e demonstrates all possible relations that must be considered according to proposed engineering methodology.

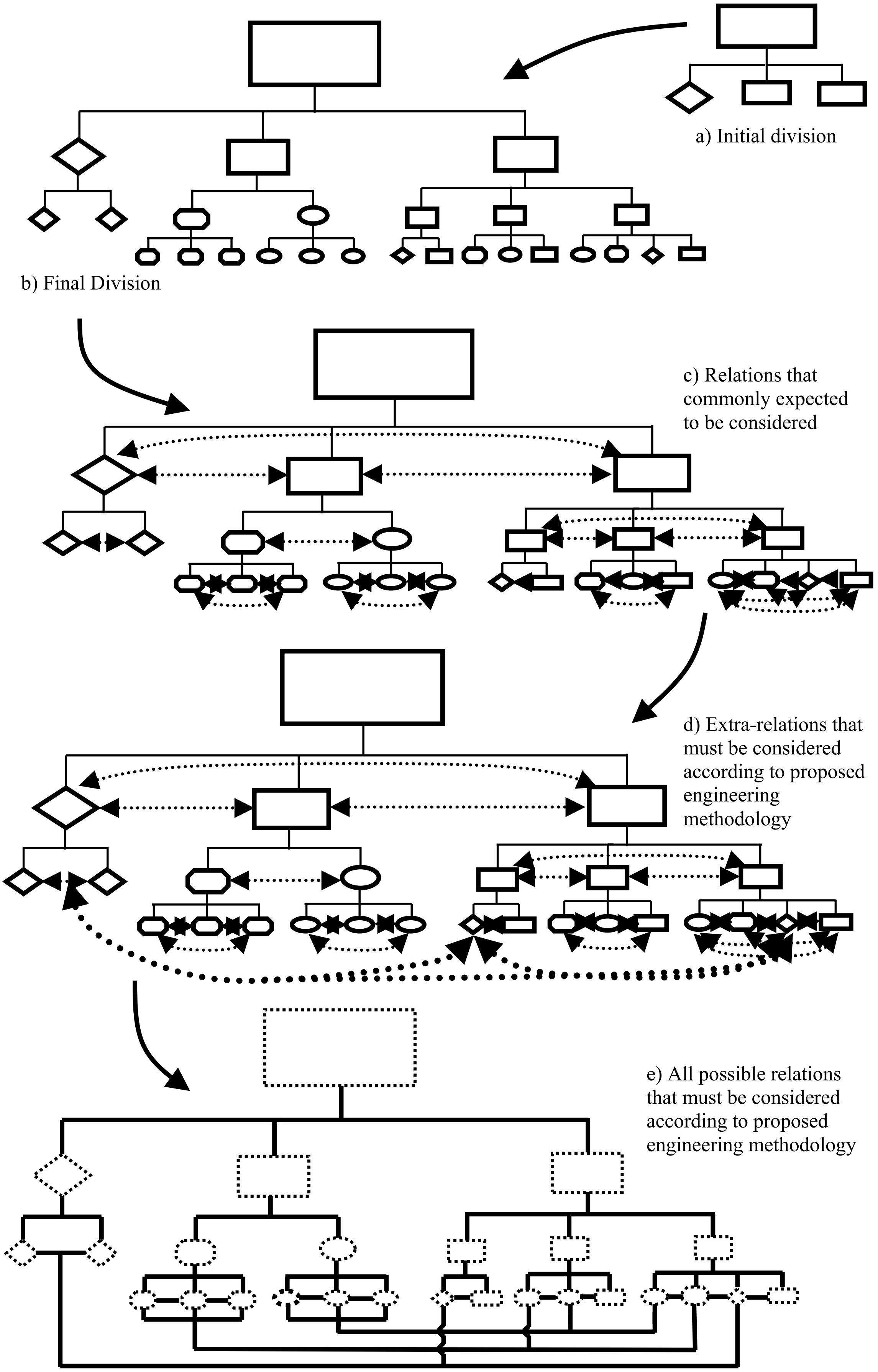


Figure 8.15: Some schematic representations for proposed conceptual design of engineering methodology

9. CASE STUDY: DESIGN OF AN INTRA-LOGISTICS SYSTEM

At this case study, I try to apply my proposed conceptual design methodology to an intra-logistics system design which was an actual design problem in Arcelik Washing Machine Plant. Starting with a predefined design problem, I try to apply all my proposals that I made in “Conceptual Design of Mechatronic Products and Processes” chapter. I need to underline here that all the flow charts which are presented at Appendix B belong to me. That is, none of these charts are prepared by another member of Arcelik and although this problem was a real design problem of Arcelik, I have tried to create my own solution with the methodology that I have developed. Nevertheless, of course, I have used some of the ideas that are created by the whole design team.

9.1 Design Problem

We need a new intra-logistic system that

- will receive the components of the production to be stored,
- will store them,
- will keep the necessary records of them so that will be able to find and retrieve the needed components as soon as possible
- will retrieve the needed components as fast as possible when needed, and
- will follow the on-going production and will feed the production lines with the needed components

Regarding requirements list is shown on Table 9.1.

Table 9.1: Requirements list

Requirements:

Geometry:
Dimensions of the storage area (maximum dimensions):
Length : 37.8m
Width : 18.4m
Height : 15m

Dimensions of the boxes of the goods (maximum dimensions):
Length : 800mm
Width : 1200mm
Height : 1600mm

Minimum storage capacity : 5.000 Euro pallets

Kinematics:
Number of retrieved components/hour : 300com./hour
Number of retrieved euro-box/hour : 400boxes/hour
Feeding time of remotest station : 10minutes

Forces:
Lifting and carrying ability of at least 100 kg at once

Energy:
Electrical, hydraulic and/or pneumatic (6 bar)

Schedule:
16 months (8 months for design and 8 months for establishment)

9.2 Concept Development

If we evaluate the design problem we see that the main design problem is the design of a system which includes some separate processes in it. Chart B.1 demonstrates the initial division of the overall function into sub-functions. As they are demanded in the main design problem, the system will carry out five main functions. These are:

- receipt of goods
- storage of the goods
- follow up of production and creating pull instructions
- retrieval of goods

- and delivery of these needed goods to the production site

After that primary division, it is impossible to define the categories of the sub-functions. Thus, some further divisions within these sub-functions are needed.

- Chart B.2 and Chart B.3 include these division activities for “receipt of goods” sub-function. In Chart B.2 initial division is made and in Chart B.3 categories of these sub-divisions are determined. Not any category is appointed to “Make the necessary quality checks” function because that function is going to be carried out by quality department out of warehouse and it can be made by any kind of activity. What is important for the warehouse of this sub-function is the quality check instruction (as its input) and the test results (as its output).
- Chart B.5, Chart B.6, and Chart B.7 exhibit further division activities for “storage of goods” sub-function. Through Chart B.5 and Chart B.6, division and category determination activities are carried out step by step and in Chart B.7 category determination is completed.
- Same activities are carried out through Chart B.10, Chart B.11, Chart B.12, and Chart B.13 for “retrieval of goods” sub-function; through Chart B.16 and Chart B.17 for “pull instruction” sub-function; and through Chart B.19 and Chart B.20 for “delivery to production” sub-function.

Categories of sub-functions are represented with the shapes and colours of task boxes in the charts such as in Figure 9.1.

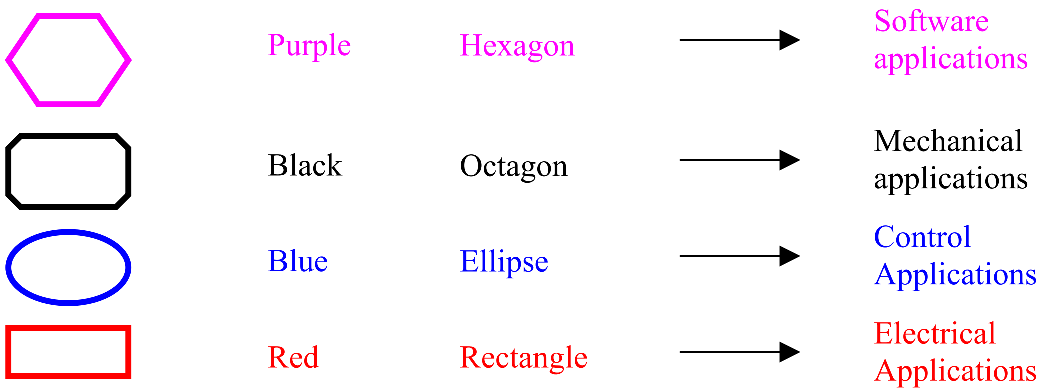


Figure 9.1: Meanings of symbols in concept charts

After all the categories of sub-functions are defined then these flow charts of main sub-functions are combined and an initial concept assembly is developed. Chart B.22 represents that initial concept assembly. As I have explained in 'Conceptual Design of Mechatronics Products' chapter, this initial concept assembly can be used for evaluating all the possible effects and extra requirements between all sub-divisions (regardless of which sub-functions they belong) in order to create a complete integration. At that point we start to find combined solutions for the whole design activity. Keeping in mind the fact that sub-functions would probably affect each other through the same category of works that they include inside, we may start to evaluation.

- The first impression that we can get from the initial concept assembly chart is that there are all for types of engineering applications in this system. First of all we need to check if we could find some combined solutions. For example, as we see in the initial concept assembly, all of the sub-functions include software applications so we must check if we could a combined solution for these applications that could carry out all these activities by it self. Therefore, we need to evaluate all the affects and constraints of related sub-functions and sub-divisions. The same activity must be carried out for control, mechanical and electrical applications as well.

After all evaluations,

- We came up to the conclusion that with a single software program we could carry out all the software applications, namely, making the records of goods, activating control systems, keeping all the related information and assessing it when needed, following the on-going production, and creating pull instructions by itself. The software system will play a supervisory role and manage the whole system.
- After receipt of goods, storage of goods and retrieval of goods can easily be made by the same controlled system. Depending on the complexity of production area which is going to be fed and the flexibility of the working principle that will carry out these works, even the delivery of goods to the production can be carried out by the same system as well. The mechanical system will have to be combined to the control system and they will act

according to the instructions of the software system. Therefore, they will have to be combined to the software system as well.

Eventually at this point, we can come up to a conclusion that it is possible to carry out all the related functions of this system by a single software program, a single control system and a single mechanical structure if the working principles can allow it. Of course, all of these applications will be supported by some electrical systems. These electrical systems will be suitable for the type of function that it is supporting. For example, electrical applications for the control system will reasonable include some sensors and actuator while they will be some databases, sensors and wires for the software system.

After making the evaluation of the initial concept assembly, having an overall view in mind, and creating an end-product focus, we can start to search for working principles. Appendix A shows all the related working principles for the designed system.

- Figure A.1 and Figure A.2 represent possible storage area applications.

  A three dimensional storage area as we see in the Figure A.1 increases the "quantity of stored goods/area of storage field" ratio. However, as we will discuss later, if we select such a system we will need different working principles for the storage of goods and delivery of goods to the production or we will need to design some special systems for extra flexibility.

  The "quantity of stored goods/area of storage field" ratio is small in a two dimensional storage area but if select that system we can store the goods and feed the production line with the same standard structures.

- Figure A.3, Figure A.4, and Figure A.5 represent standard handling systems.

  For a three dimensional storage area a stacker crane is essential. If we want to make the storage and retrieval of goods with the field cranes, we need to make a special design for field cranes for extra flexibility.

  A conveyor can be used for delivery of goods but its flexibility is low and in many cases a human entry is needed for loading and unloading of goods.

- When we come to evaluate the software applications, we need to evaluate the currently working systems of production, planning and software applications because this designed system is an after-added system and it has to be adapted to the current systems or the current systems have to be adapted to this newly designed system.

First of all, Arcelik uses SAP as an ERP (enterprise resource planning) software. Therefore, all the product trees, production plans and stock information are kept by SAP. If we do not keep these data in the database of the software program that is going to be designed, we not only speed up the work of the program but also we prevent an inefficiency of making the same work for twice. Also, quality control information of entering goods is kept in SAP database as well. Thus, we can receive these data from SAP database too.

However, in order to receive all these data from SAP database we need to design another program for transferring the information from SAP database to warehouse database and from warehouse database to SAP database.

On the other hand, through this evaluation we catch the idea that ‘checking of on-going production’ and ‘checking the number of available goods’ activities of ‘pull instruction’ sub-function can be carried out by the software system with the mediation of a few sensors. Having the plans of on-going production and receiving the information of the produced goods, it is easy to assess the number of available goods and check the on-going production by software system.

After finding all working principles for sub-functions and sub-divisions, we may combine them in order to create the principle solution.

- Figure A.1, Figure A.2, Figure A.3, Figure A.4, Figure A., and Figure A.6 represent all the possible working principles and Figure A.7 represents what we have selected in Arcelik.

  We have selected the three dimensional storage area in order to have a big “quantity of stored goods/area of storage field” ratio.

  We have selected to store and retrieve the goods by stacker cranes and separate the work of feeding the production line from these activities because otherwise we had to design some special field cranes which would be too expensive.

We decided to make the delivery of the goods by a combination of conveyors and field cranes considering place restrictions that these structures will be established in.

Therefore, even though along the embodiment design phase some changes can be made, the designed intra logistic system will look like somehow to Figure A.7 at the end.

Together with all above selection and combining activities, the initial concept assembly is detailed as well. Chart B.4, Chart B.8, Chart B.9, Chart B.14, Chart B.15, Chart B.18 and Chart B.21 represent these activities. After all, the final concept assembly is developed in Chart B.23.

At this point conceptual design activities are finished and embodiment design phase starts.

10. FINDINGS AND CONCLUSION

Under the lights of a wide range literature examination I have evaluated the subject “Use of Mechatronics in Product and Process Design”. Here below are all my findings:

- In order to create actual mechatronics, the design team must be fully structured by or at least must include some “*mechatronics engineers*”.

  These mechatronics engineers must be multi-disciplined engineers who would know the constraints, priorities, strengths and weaknesses of all related engineering disciplines; who would know at least a little bit of everything of the jargons of these disciplines as well as marketing, sales, finance and other related groups and so create a bound between them by establishing a common interface language; who would get over conflict through negotiations and make the best trade-offs without being impressed by the pride of their background; and who would have managerial skills.

- Mechatronics engineers must be mainly situated in “clarification of the task phase”, “conceptual design phase”, and “embodiment design phase” of engineering design methodology. Omitting the fact here that they may be the technology pursuit team of the organisation, they are not expected to play any important role either at “product planning phase” or at “detail design phase”.
- The structure of mechatronic design team requires at least a matrix organisation and a project organisation would make the best structure. In any case, mechatronics engineers are expected to be the team leaders of each engineering group.
- Mechatronics engineers would become better CTOs than a single disciplinary specialist or generalist.

- In order to be able to design actual mechatronics, the designed system must be considered as a whole and designers must adopt the end-product focus and keep it alive throughout the whole design activity.
- While developing the concept of the design through the conceptual design phase, the categories of the sub-functions must be defined according to the general information that “data processing and communication activities can be better carried out by software applications; control and coordination activities can be better carried out by control applications; material movement, power transmission, housing and aesthetics can be better provided by mechanical applications; and electrical applications take place in everywhere that electricity is consumed, stored, processed, or produced” and solution ideas must be tried to be found within these categories first if possible.

  If such an activity is successfully carried out then the initial inclinations and common solution ideas can be broken down; an overall view of the whole design can be obtained at an early stage and combined solutions can be found; and evaluation of the possible effects and extra requirements between sub-functions becomes easy.
- Conceptual design phase of engineering design methodology must direct the design team to evaluate all the possible effects and extra requirements between all sub-divisions (regardless of which sub-functions they belong) in order to create a complete integration and synergy.
- For the design of actual mechatronics, design team must create an overall view of the whole design as early as possible in the design activity and find combined solutions at the beginning if possible.

After all my work, I may easily say that although neither its name nor its history is new, mechatronics is a developing subject and not completed yet. It is not even clear to what end points it may reach. Future developments in electronics, control and software technologies will set a route to the journey of mechatronics in the history.

With this master’s thesis, I have evaluated the inclusion of mechatronics engineers in design and technology pursuit as well as conceptual design of mechatronics components. While making my proposals I have depended on my definition for mechatronics engineers. However, it is still not clear how to educate such kind of mechatronics engineers and who can educate mechatronics engineers at first actually. The answer of these questions can be the subject of another study.

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APPENDIX_A

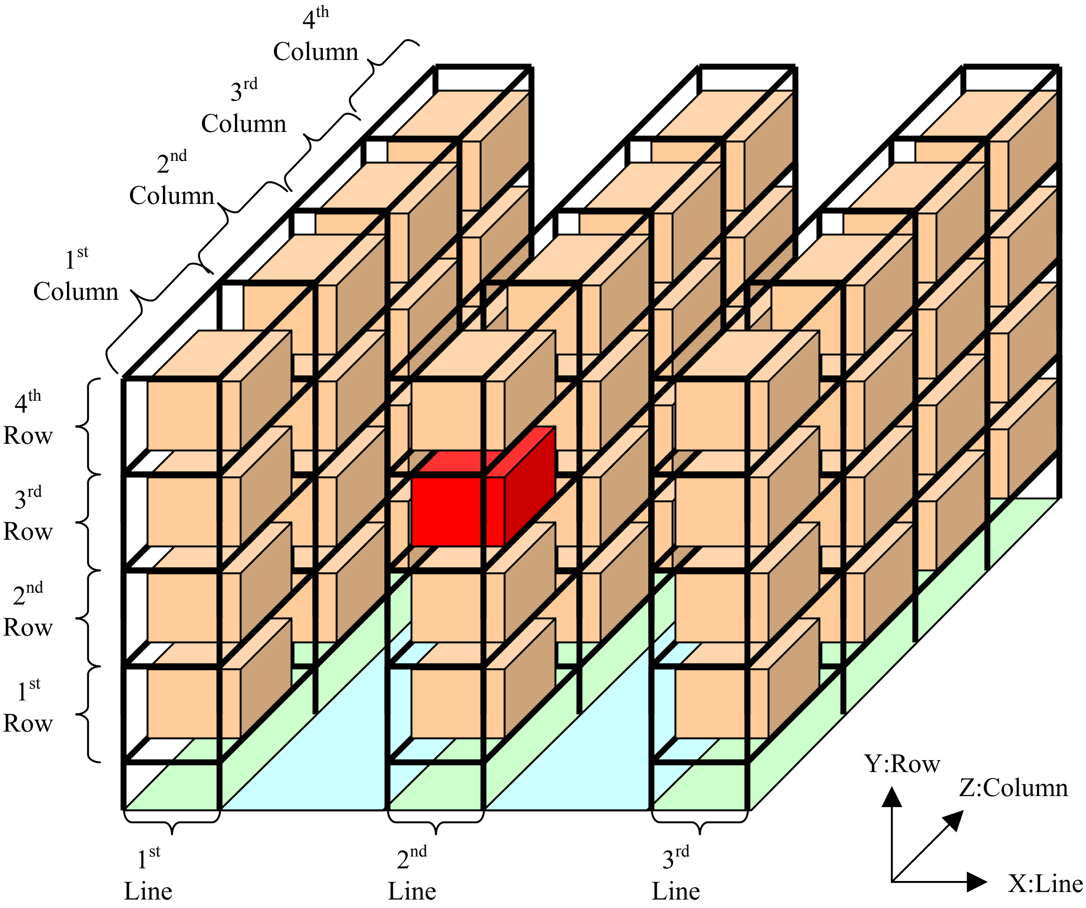


Figure A.1: Three dimensional storage area. Position of red box: (2;3;1)

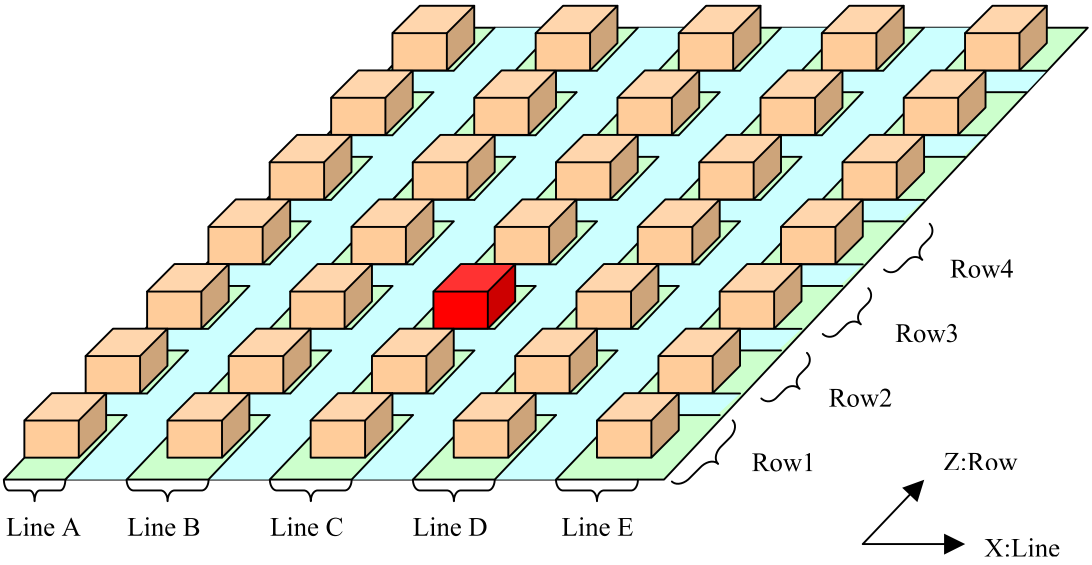
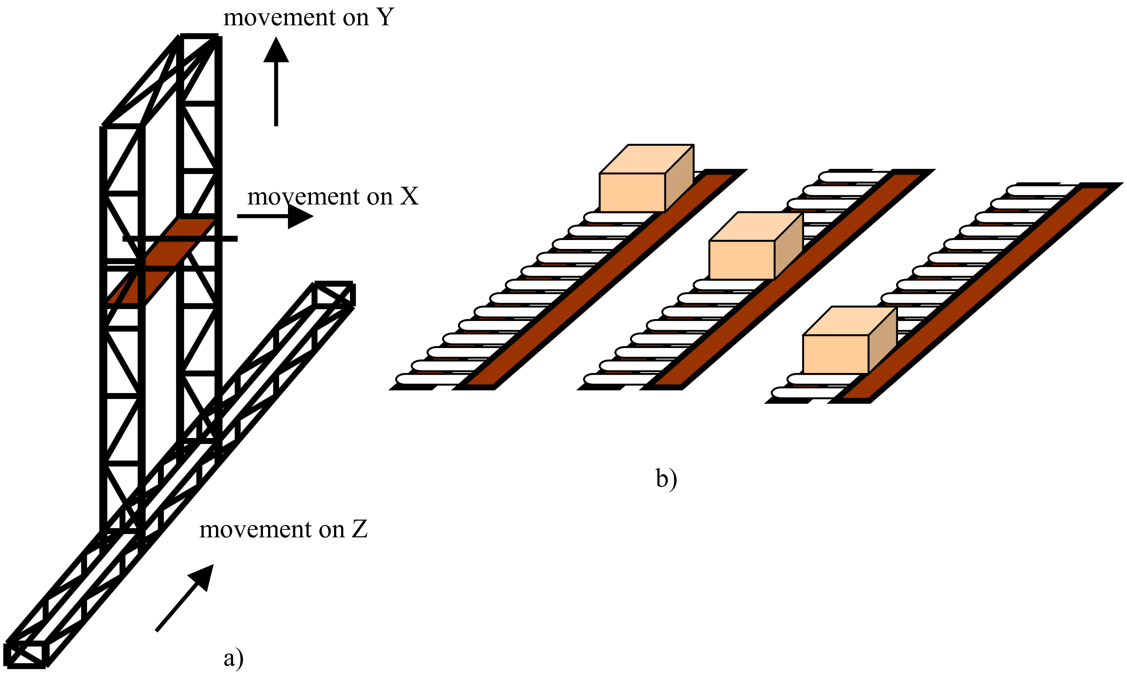


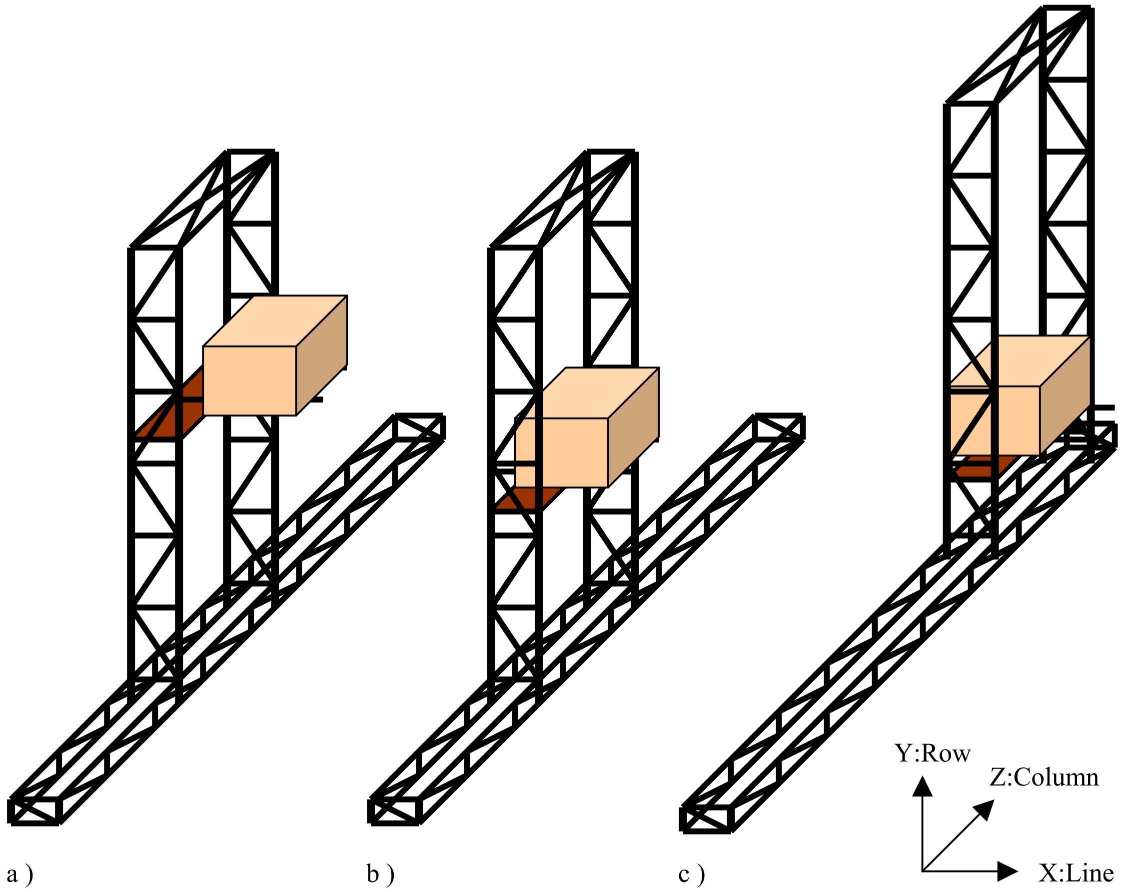
Figure A.2: Two dimensional storage area. Position of red box :(C;3)



a)

b)

Figure A.3: Schematic representations of a stacker crane (a) and a conveyor (b)



a)

b)

c)

FigureA.4: Schematic representation of three dimensional movement of a stacker crane. a) Initial position b) Second position after movements through X and Y directions. c) Third position after movement through X, Y and Z directions

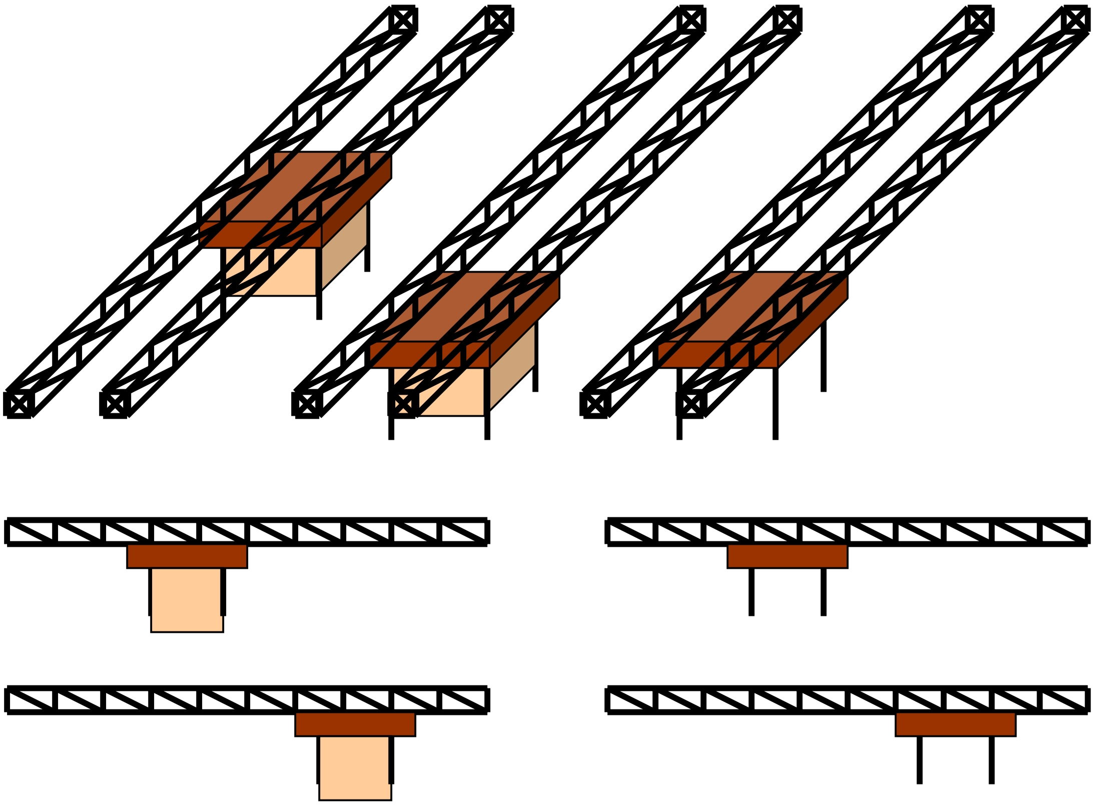


Figure A.5: Schematic representations of a field crane

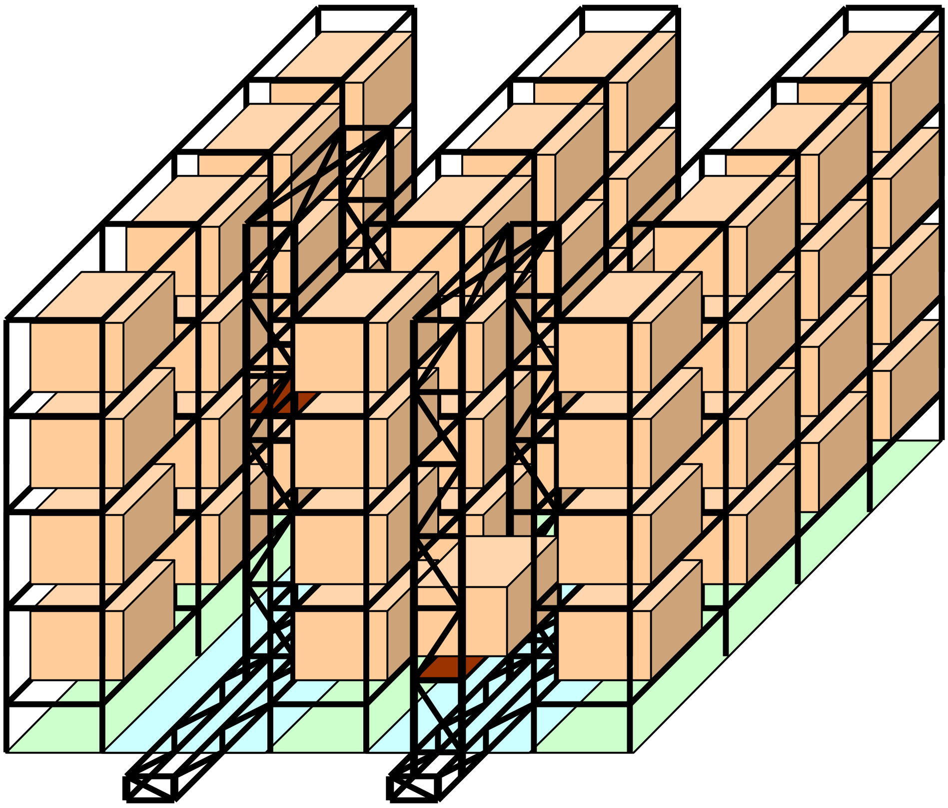


Figure A.6: Figure: Three dimensional storage area with stacker cranes

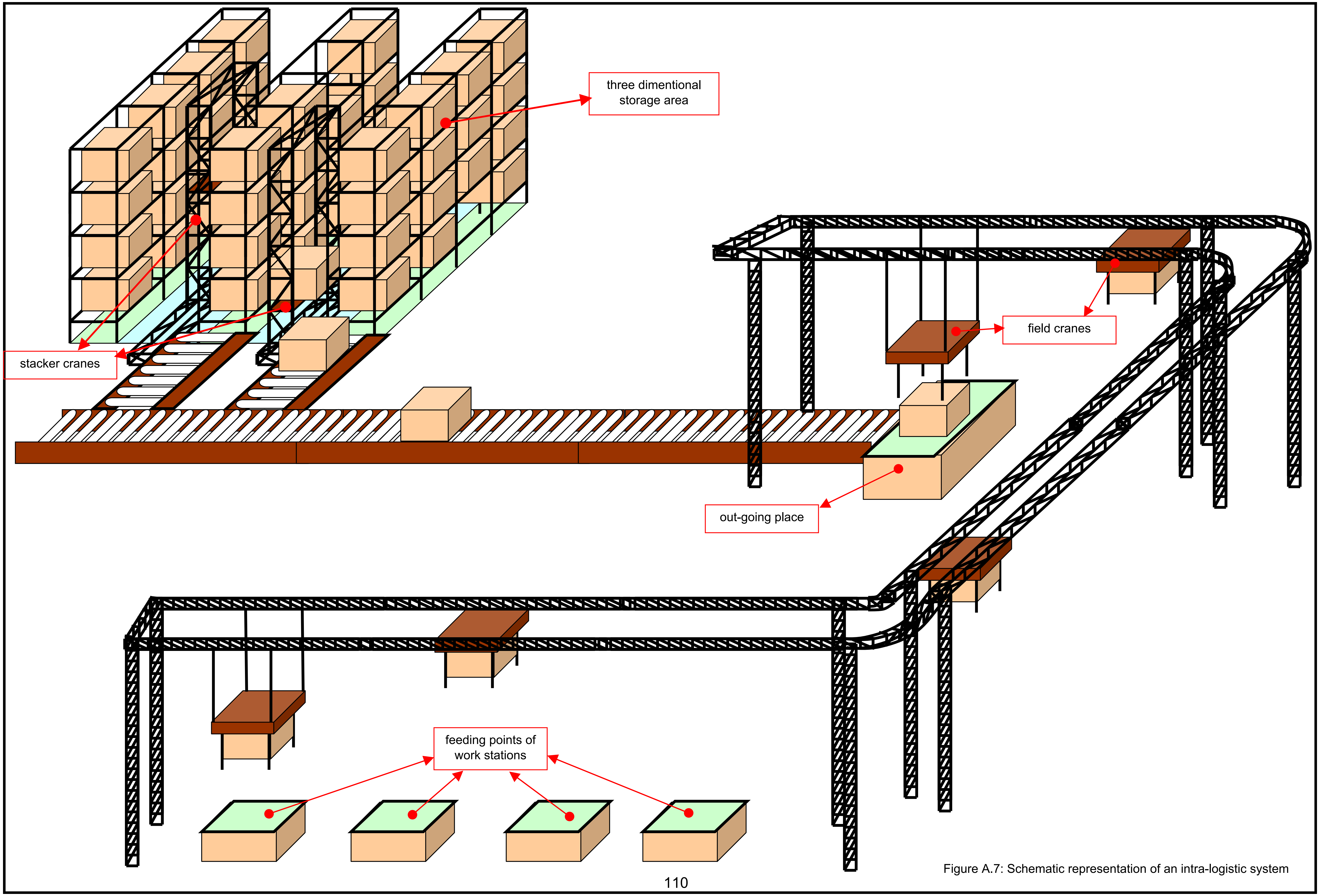


Figure A.7: Schematic representation of an intra-logistic system

APPENDIX_B

Chart B.1: Initial division from overall function to sub-functions

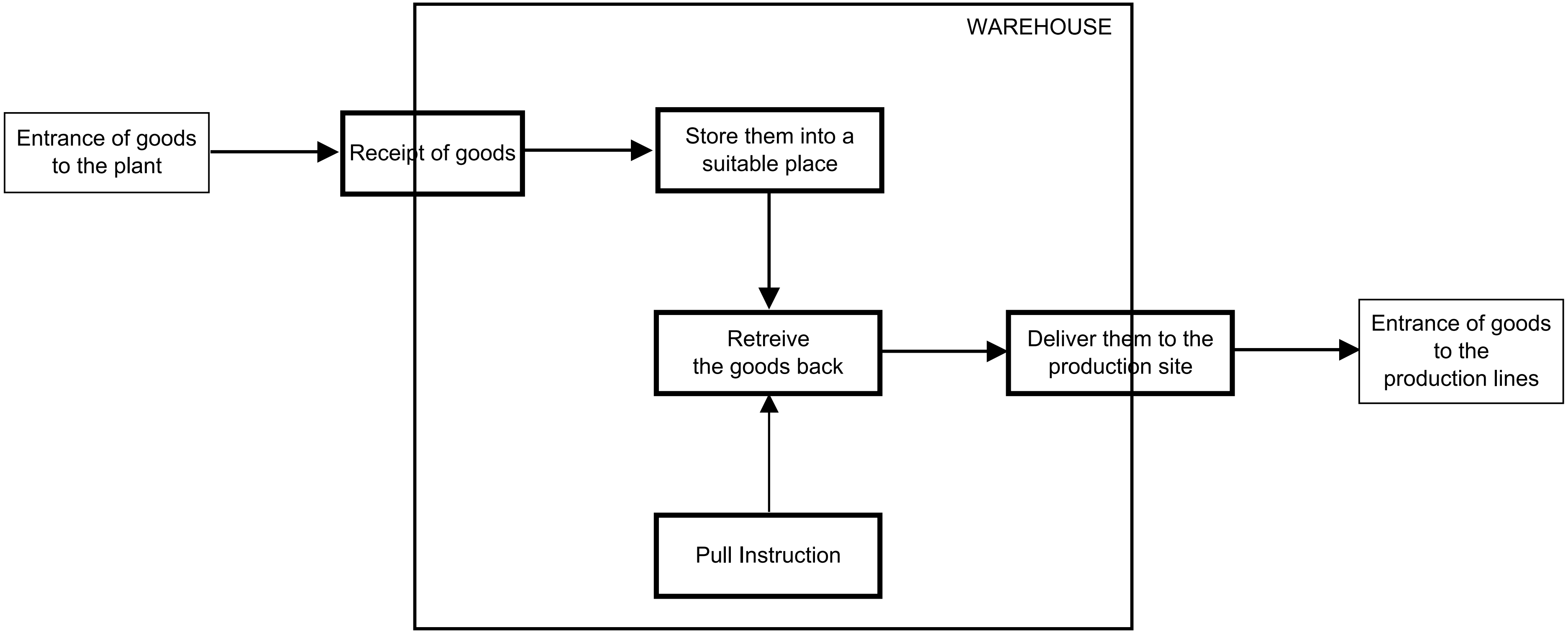


Chart B.2 :Receipt of Goods

1st Draft

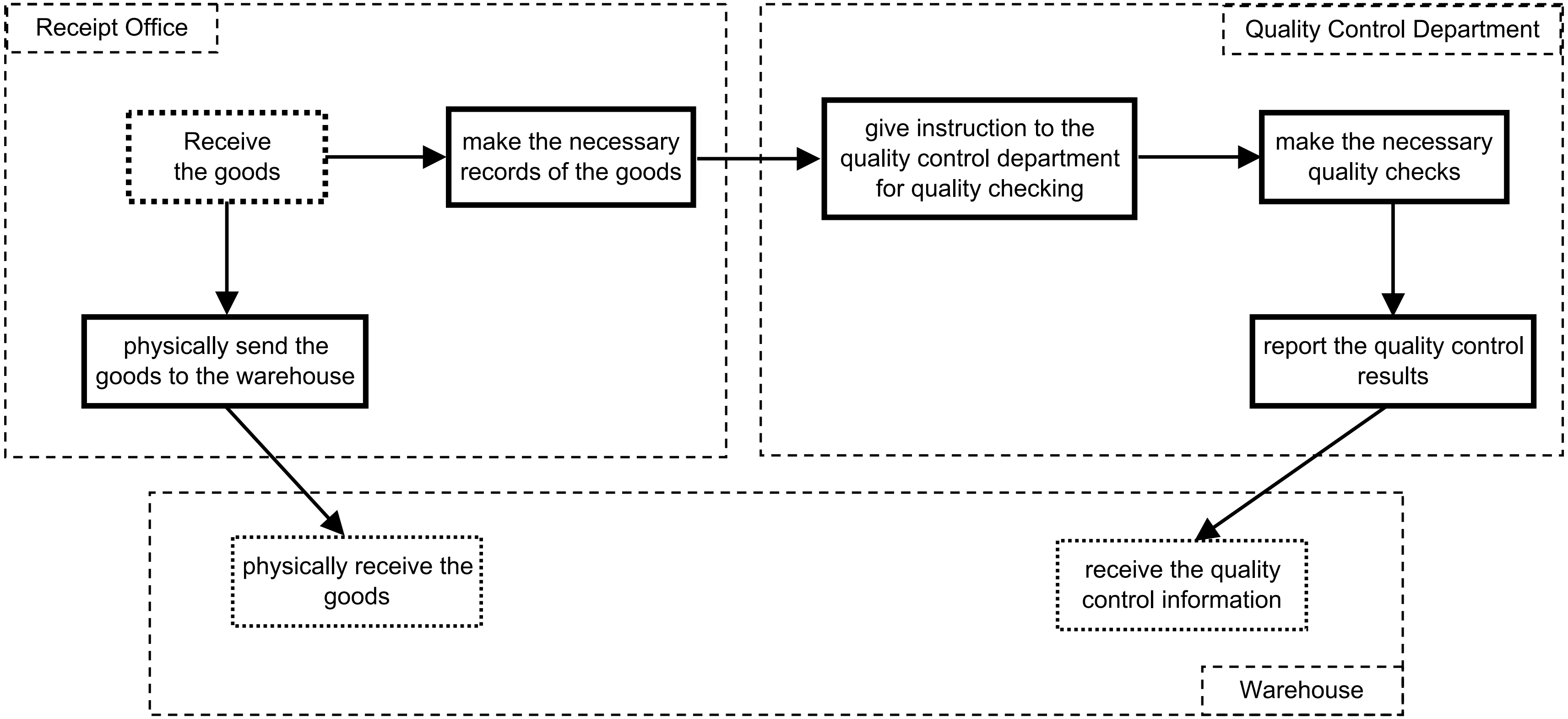


Chart B.3 :Receipt of Goods

2nd Draft: Category determination completed

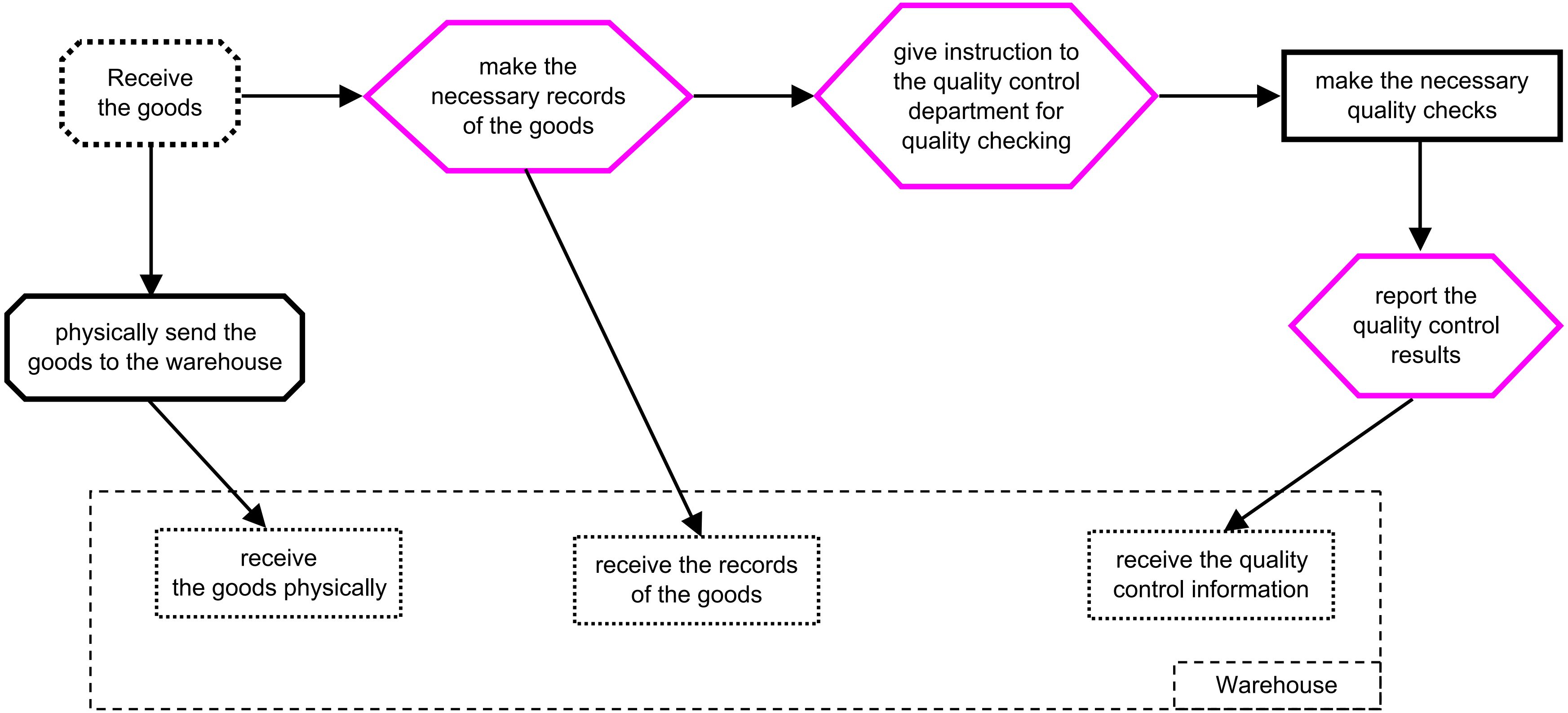


Chart B.4 :Receipt of Goods

Final Draft

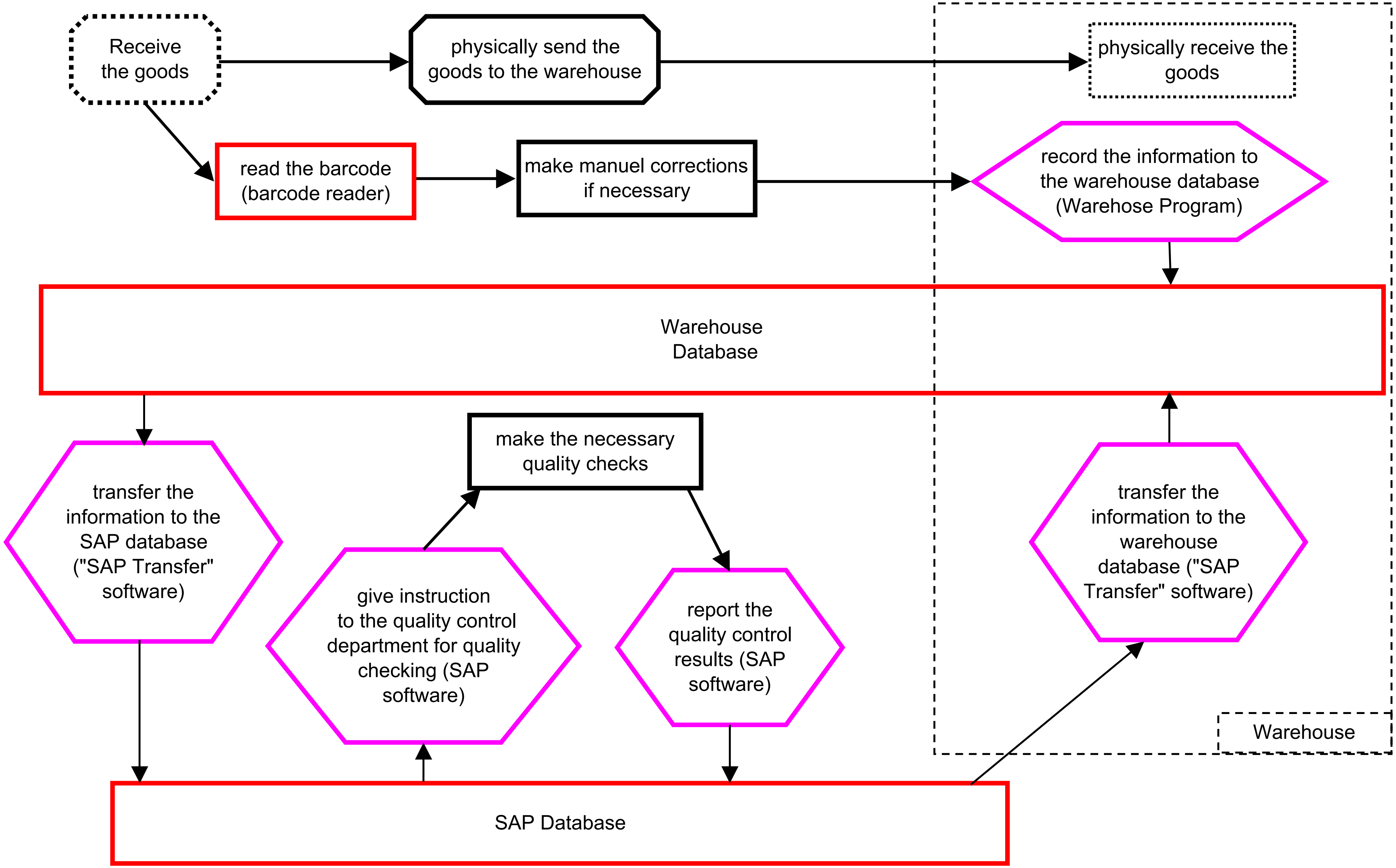


Chart B.5: Storage of Goods

1st Draft

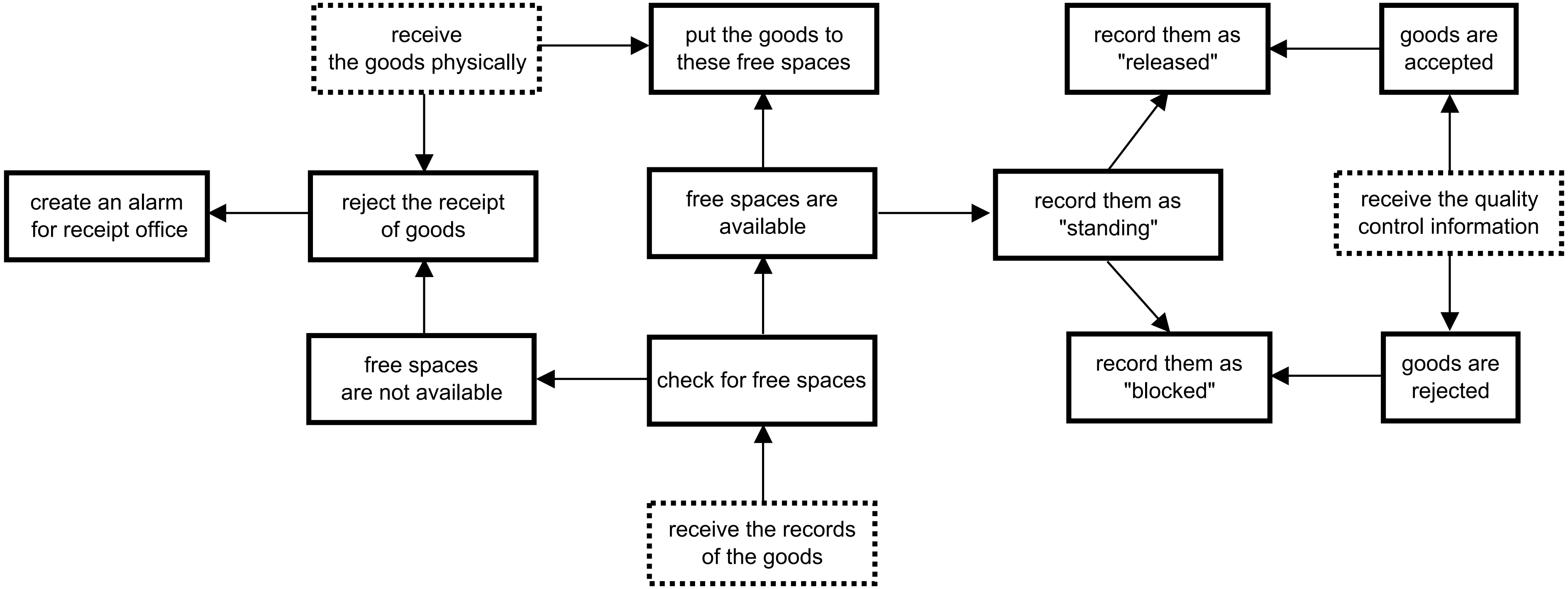


Chart B.6: Storage of Goods

2nd Draft

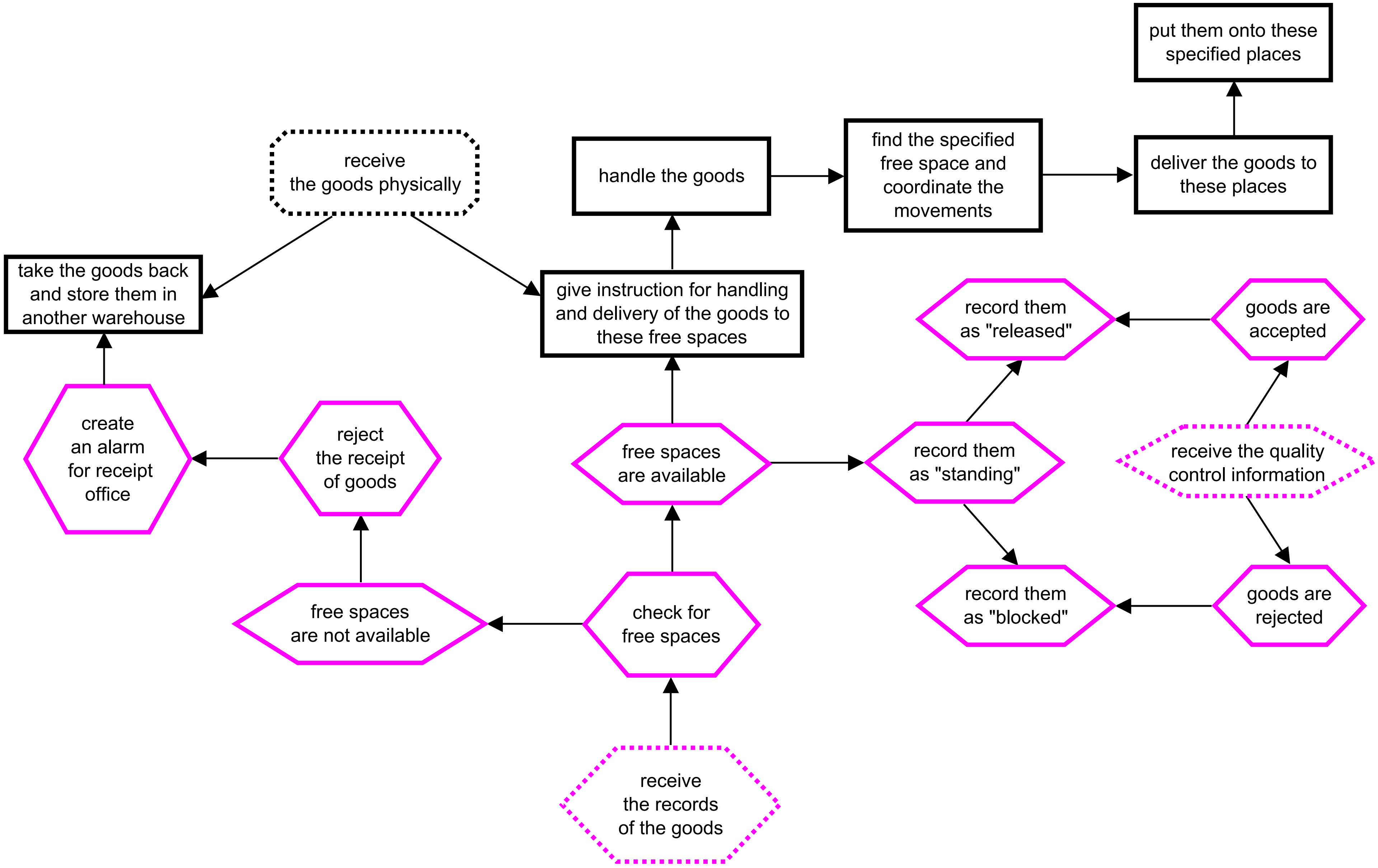


Chart B.7: Storage of Goods

3rd Draft: Category determination completed

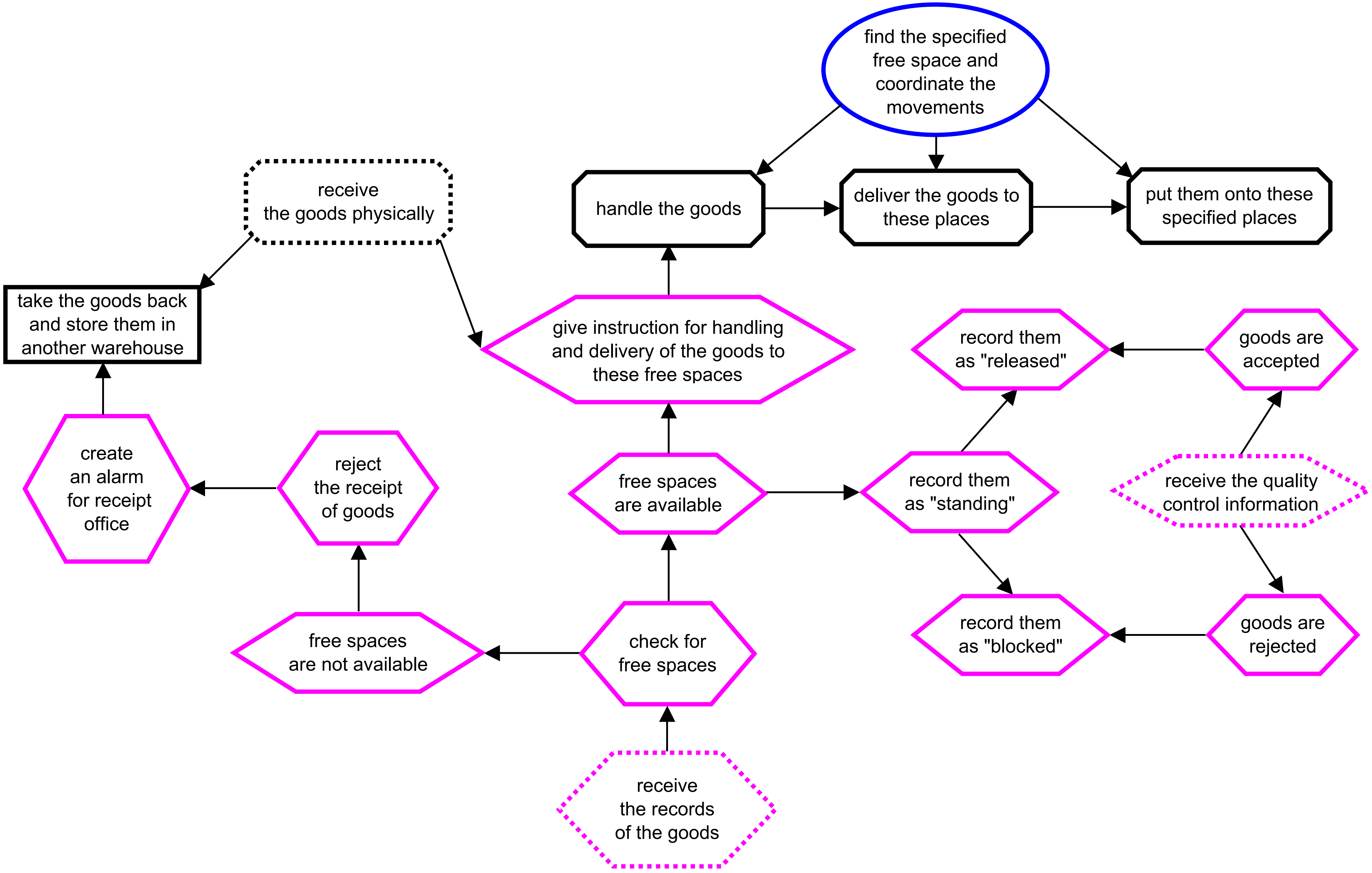


Chart B.8: Storage of Goods

4th Draft

Chart B.9: Storage of Goods

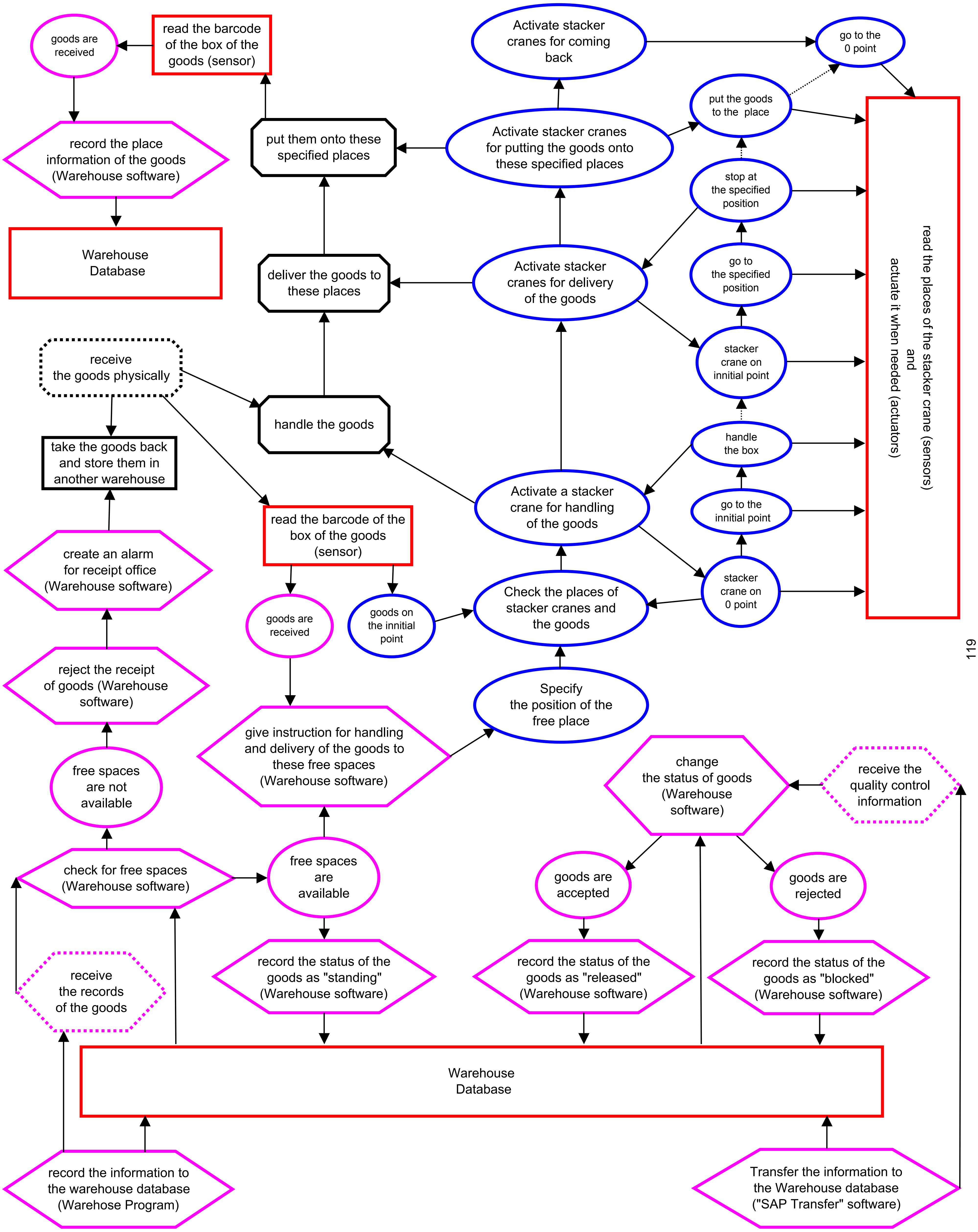


Chart B.10:Retreival of Goods ***1st Draft***

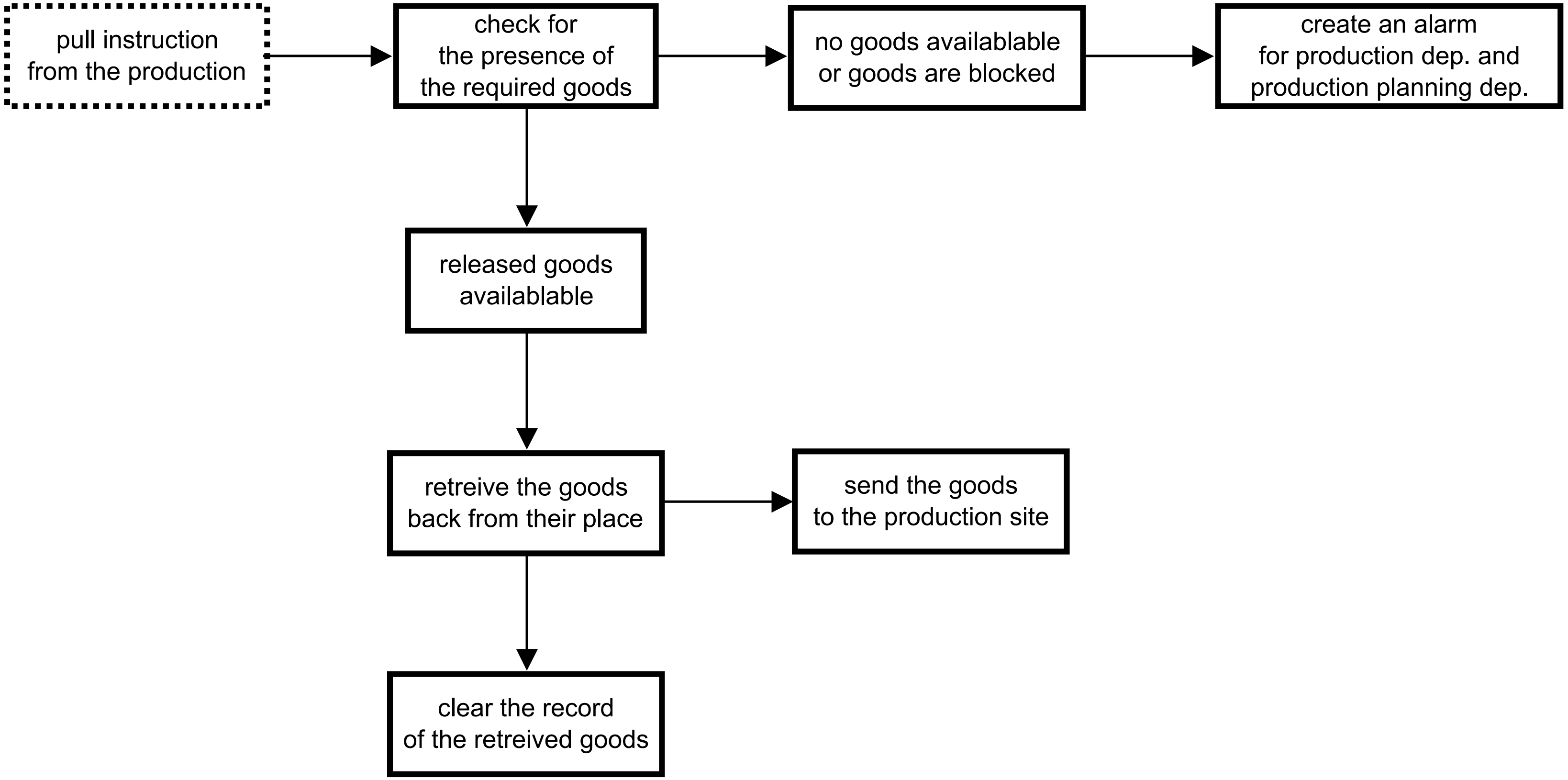


Chart B.11: Retreival of Goods

2nd Draft

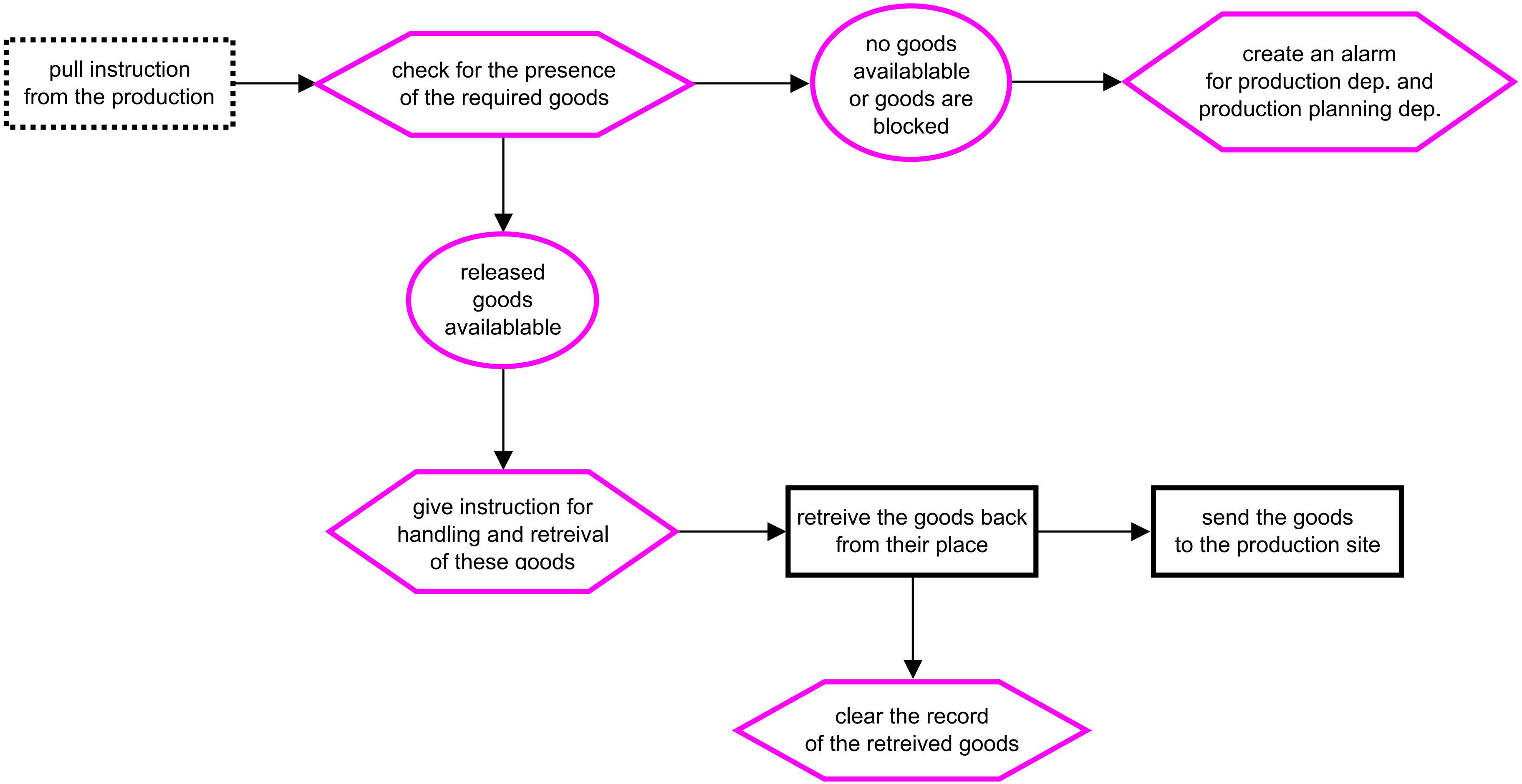


Chart B.12: Retreival of Goods

3rd Draft

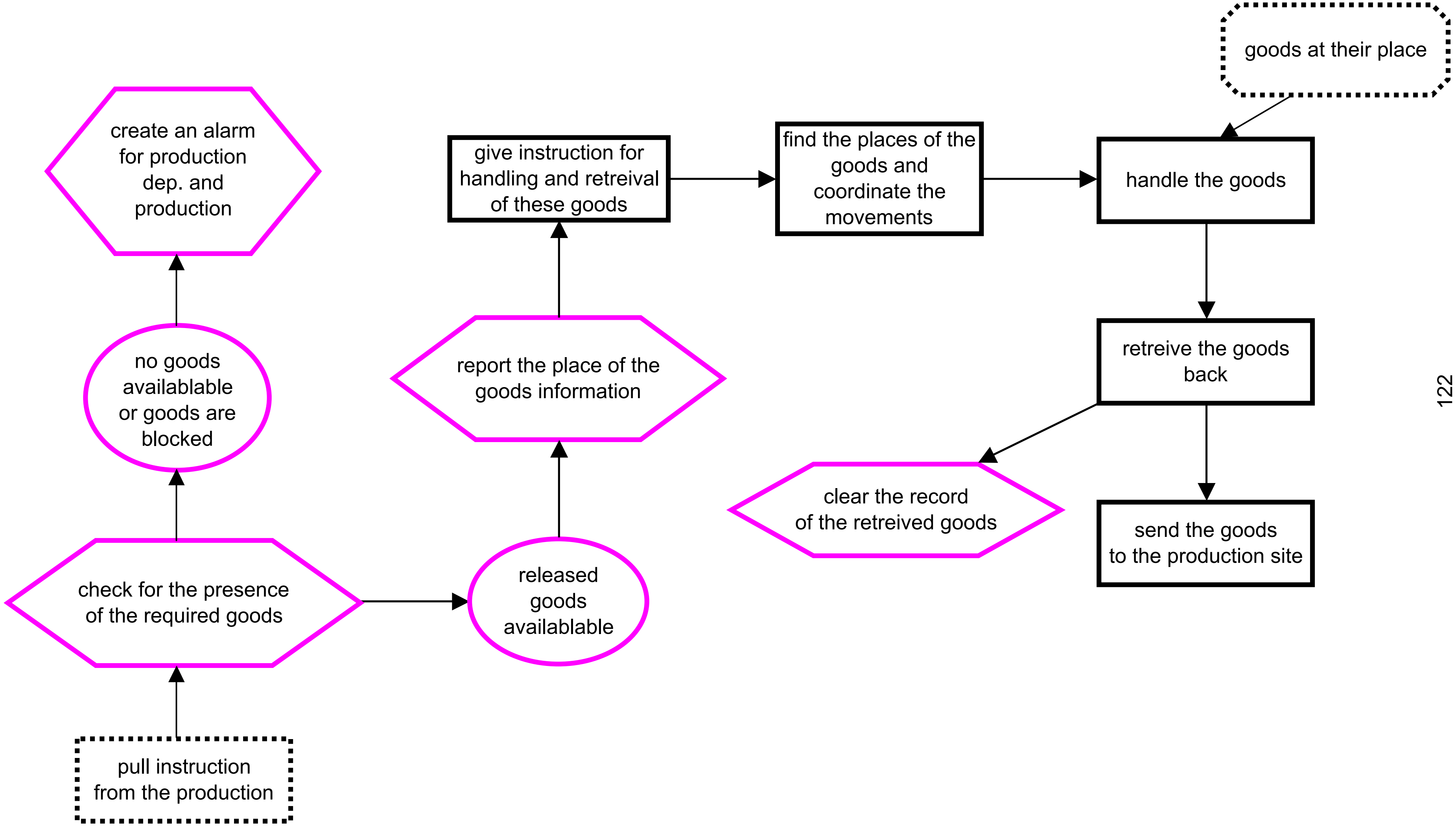


Chart B.13: Retreival of Goods

4th Draft: Category determination completed

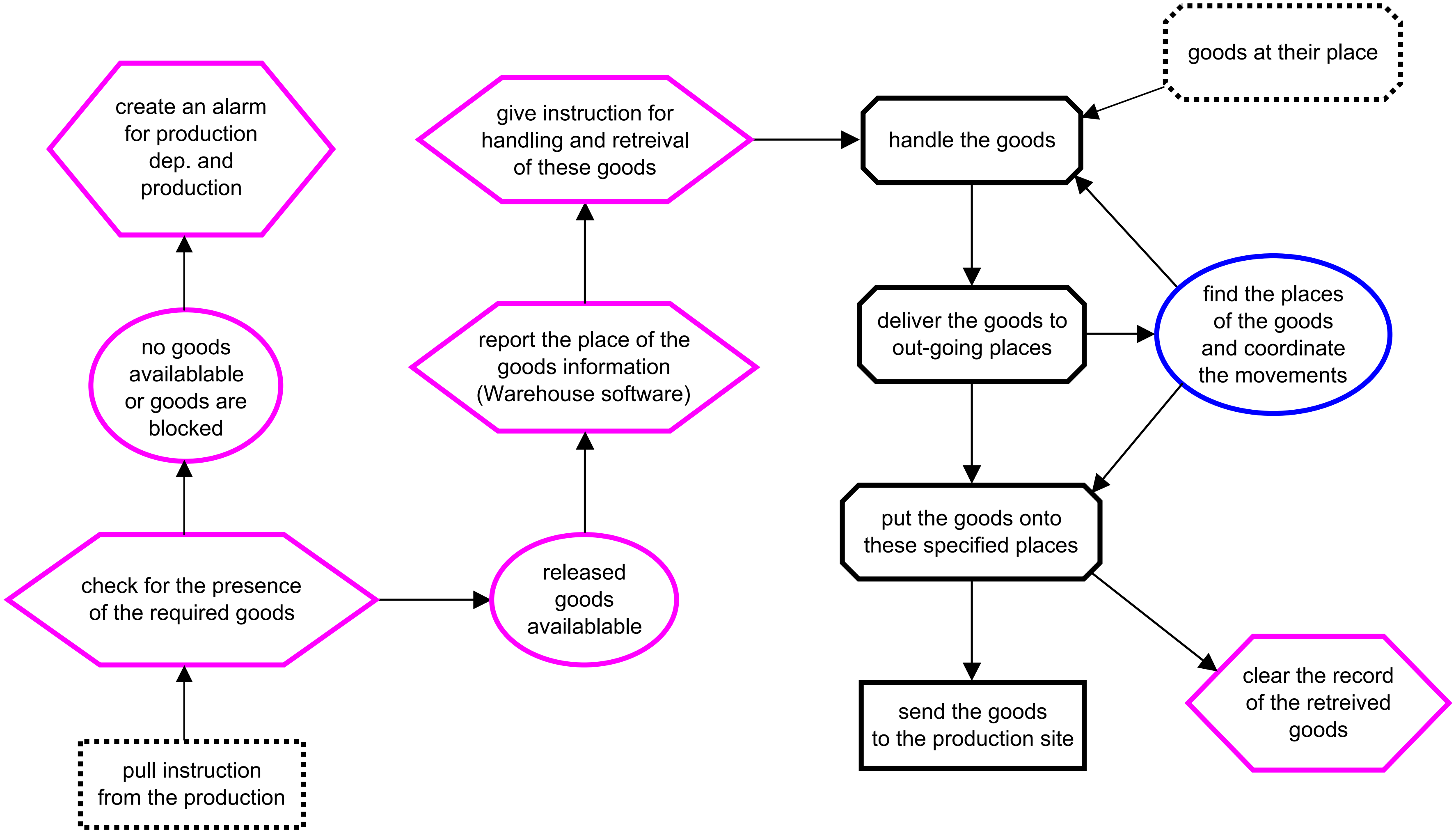


Chart B.14: Retreival of Goods

5th Draft

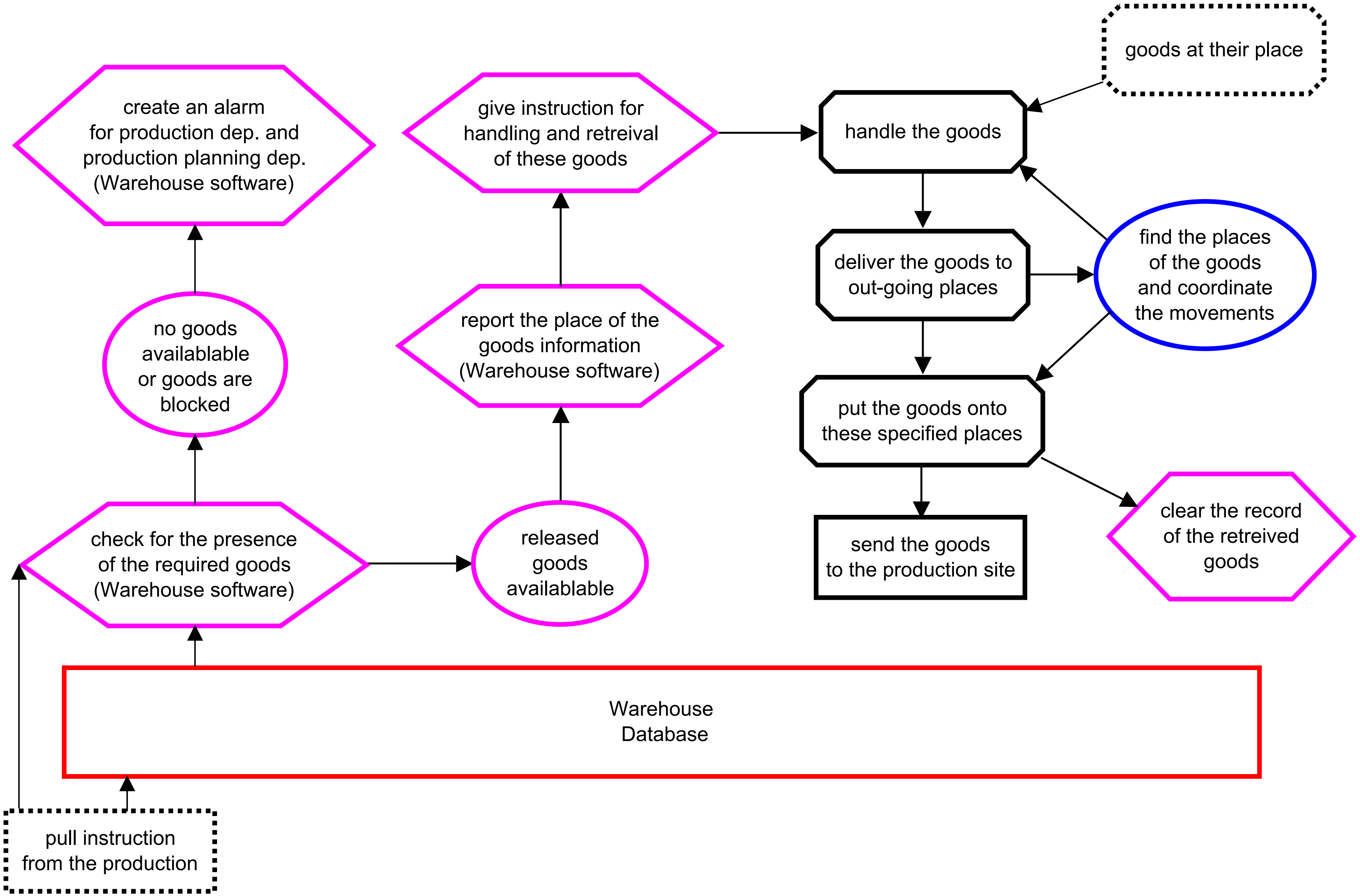


Chart B.15: Retreival of Goods

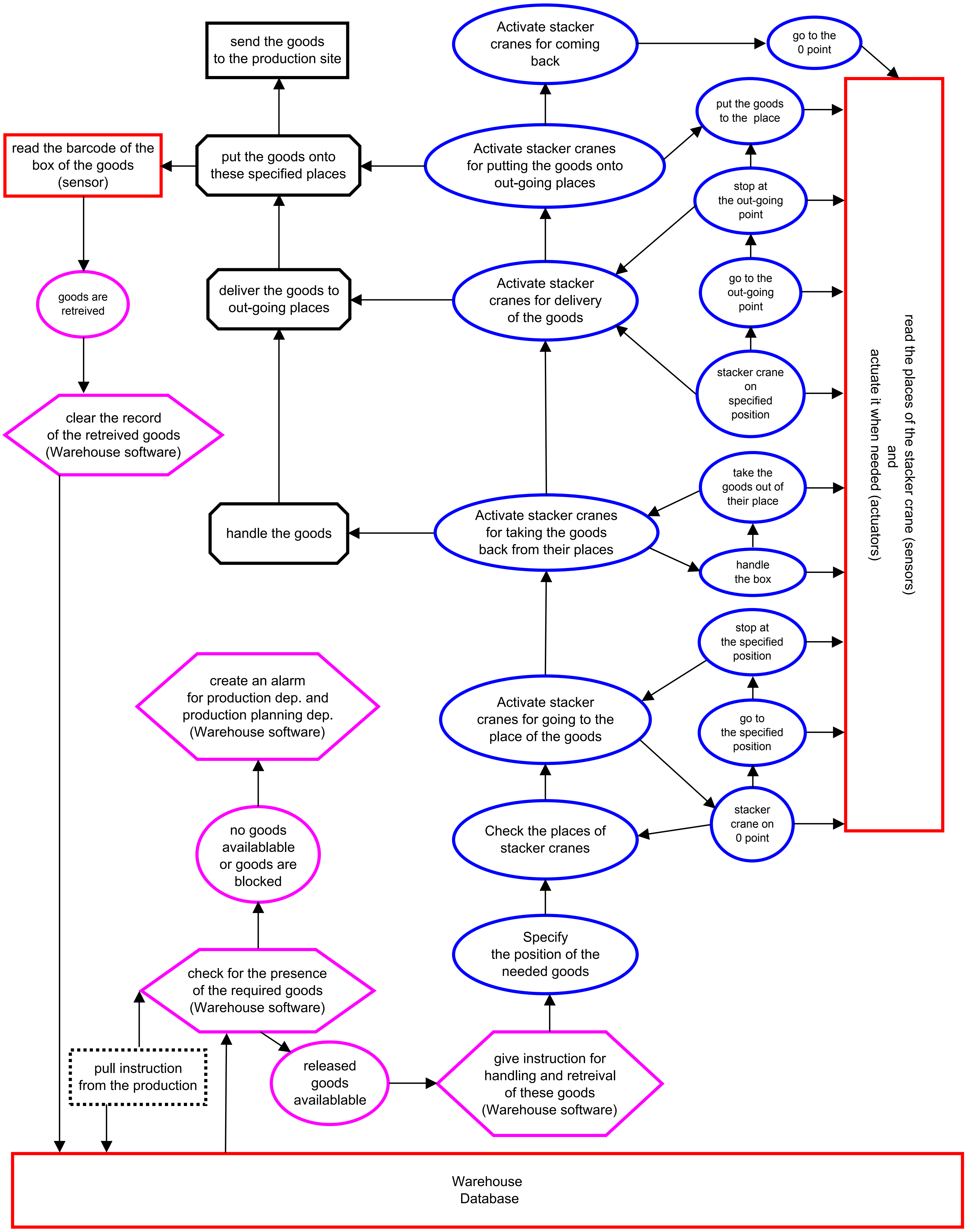
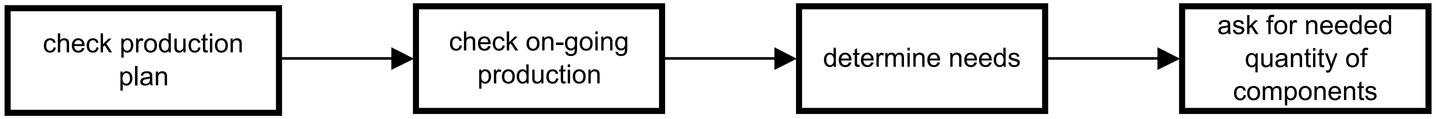


Chart B.16: Pull Instruction

1st Draft



Pull Instruction

2nd Draft

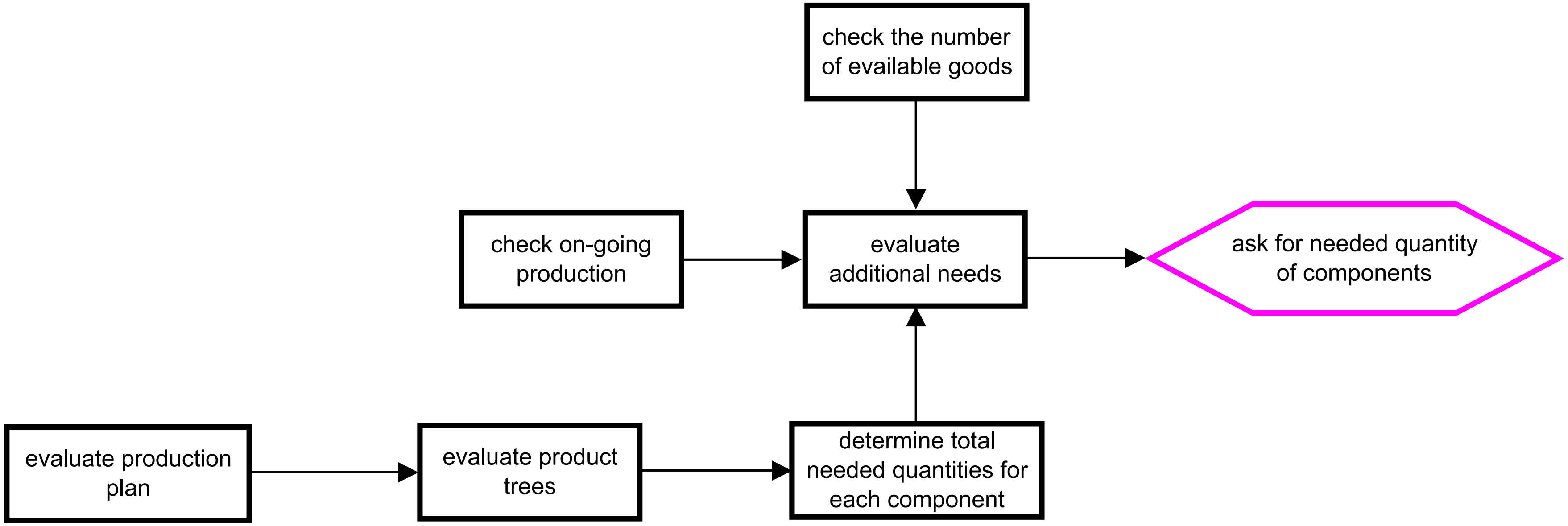


Chart B.17: Pull Instruction

3rd Draft: Category determination completed

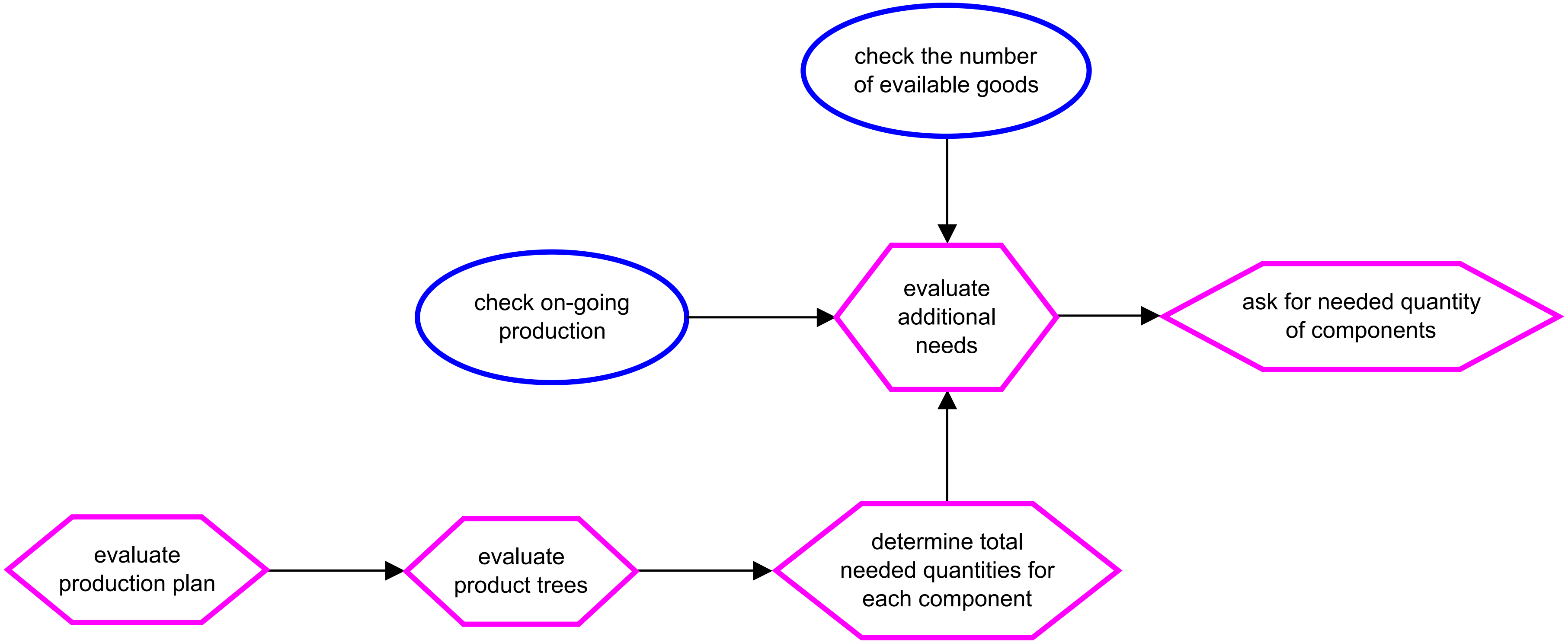


Chart B.18: Pull Instruction

Final Draft

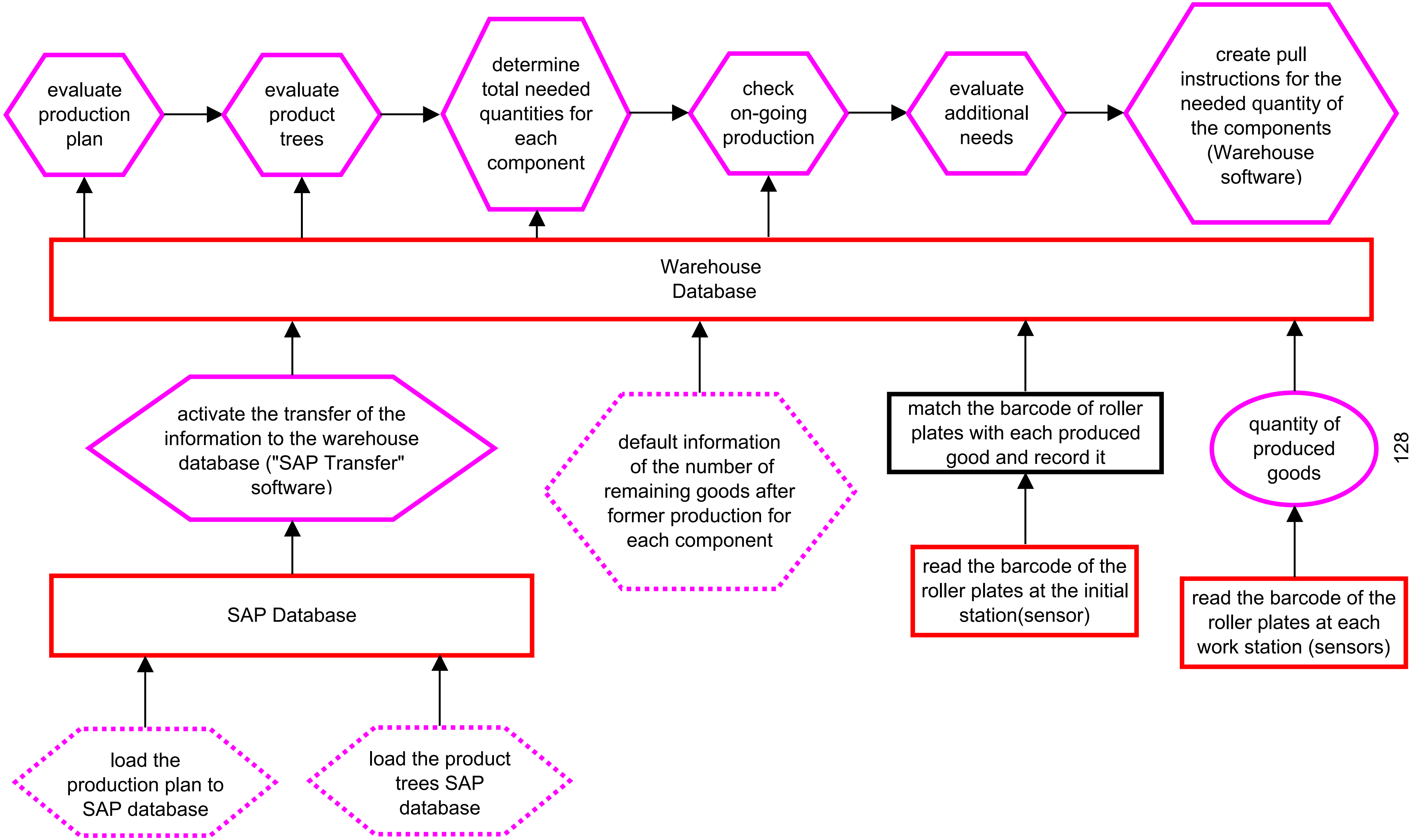


Chart B.19: Delivery to Production

1st Draft

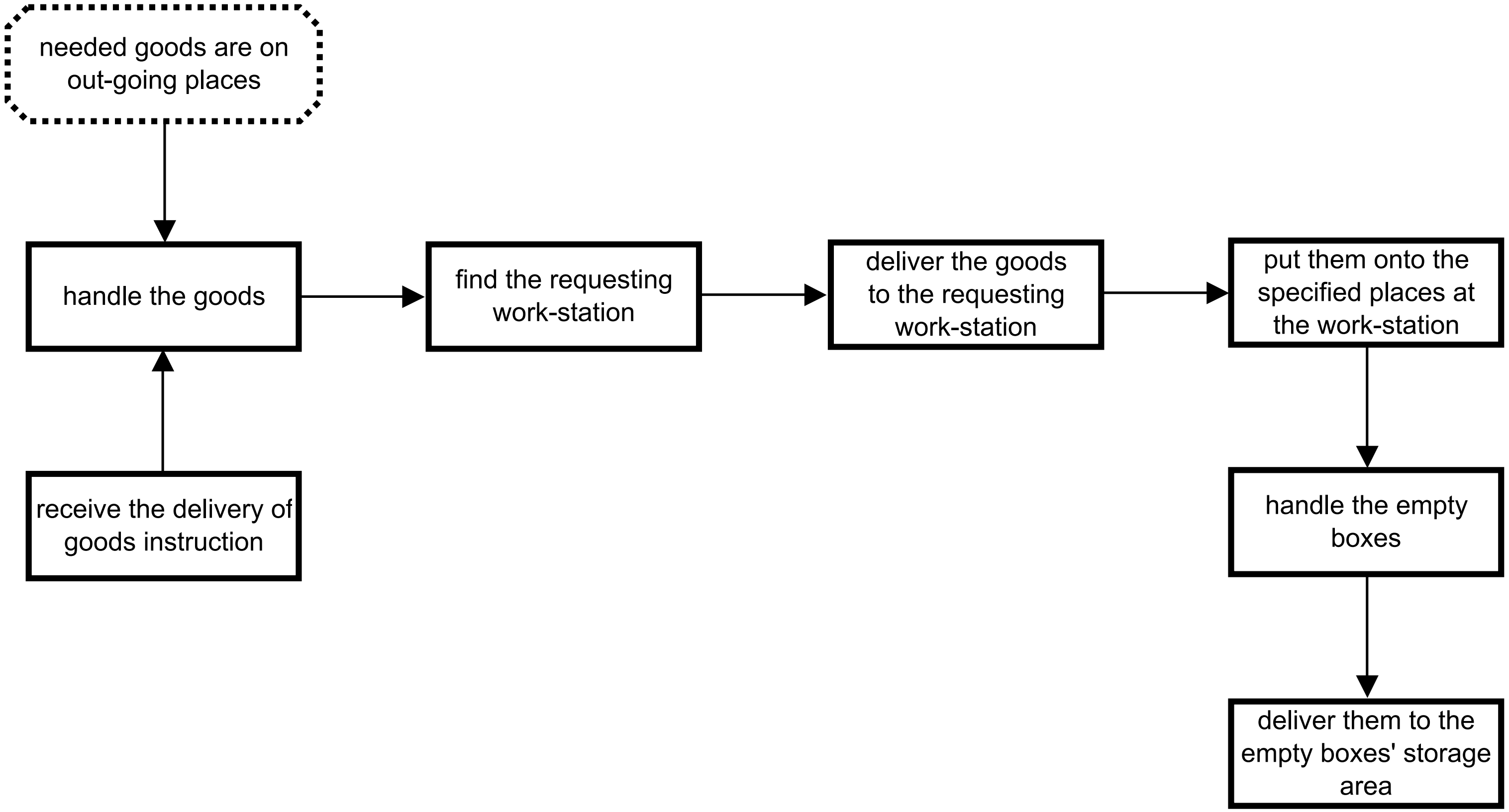
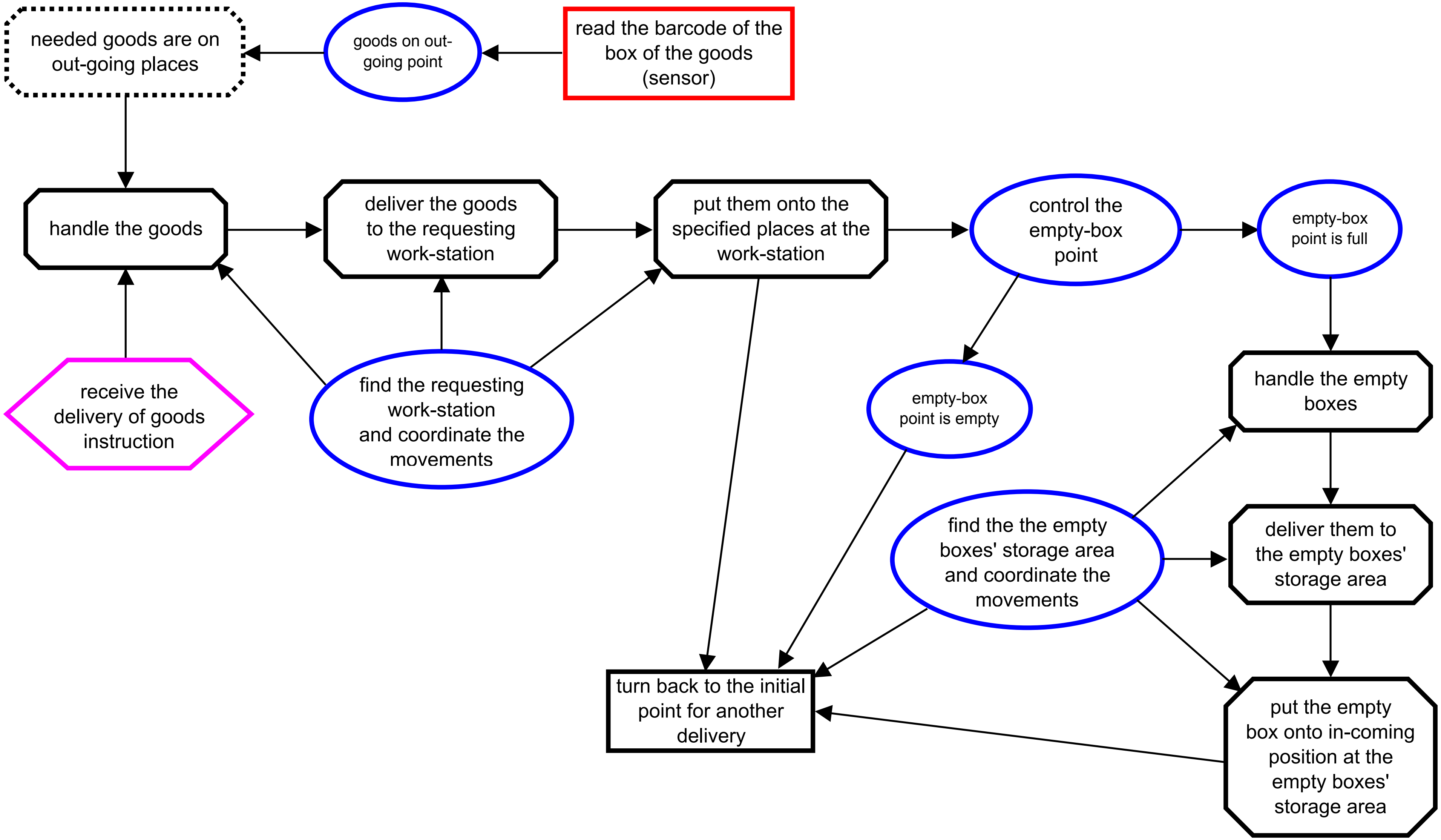


Chart B.20: Delivery to Production

2nd Draft: Category determination completed



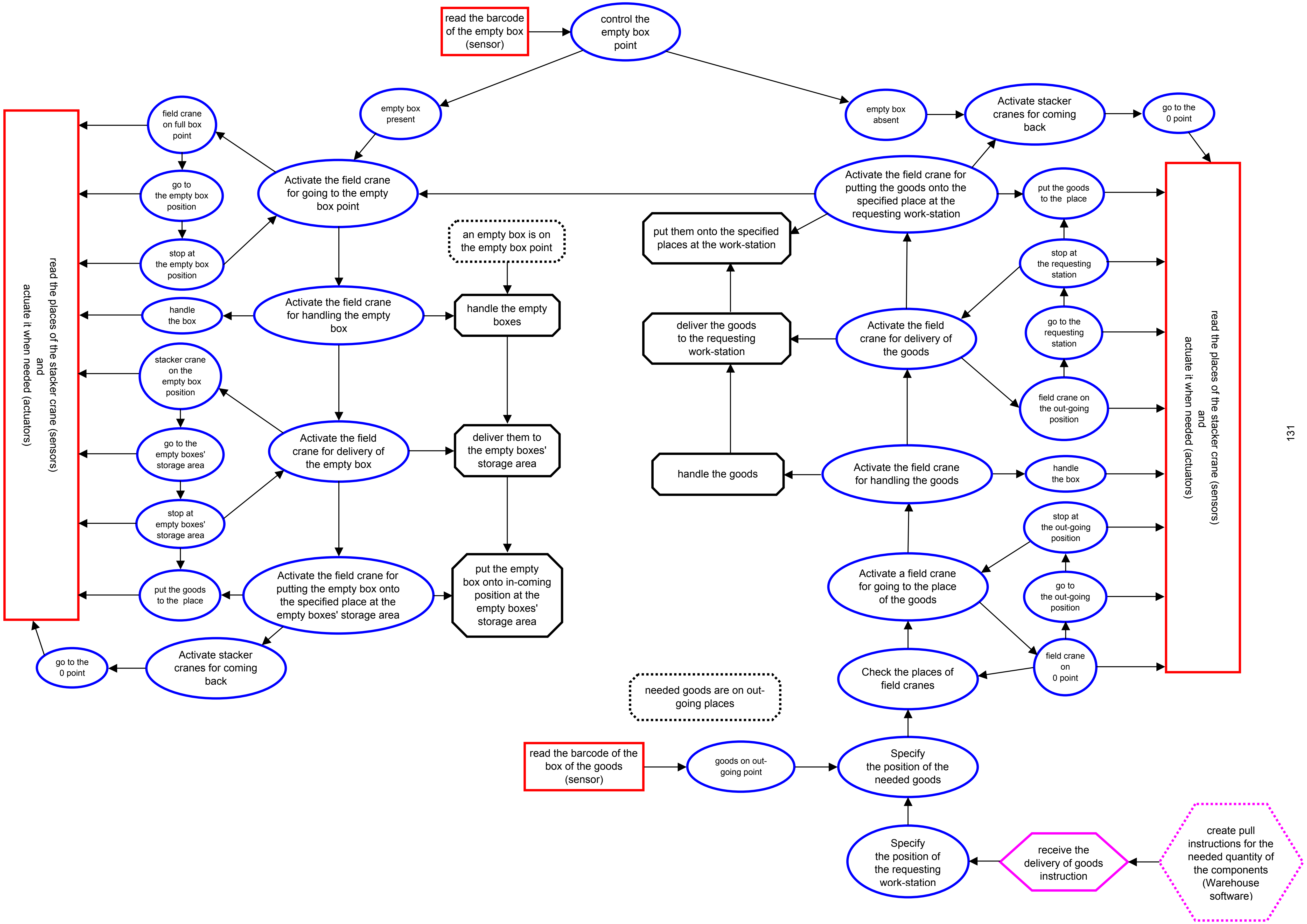

read the barcode of the empty box (sensor)
control the empty box point
empty box present
empty box absent
Activate stacker cranes for coming back
go to the 0 point
field crane on full box point
go to the empty box position
stop at the empty box position
Activate the field crane for going to the empty box point
an empty box is on the empty box point
handle the box
Activate the field crane for handling the empty box
handle the empty boxes
stacker crane on the empty box position
go to the empty boxes' storage area
stop at empty boxes' storage area
Activate the field crane for delivery of the empty box
deliver them to the empty boxes' storage area
put the goods to the place
Activate the field crane for putting the empty box onto the specified place at the empty boxes' storage area
put the empty box onto in-coming position at the empty boxes' storage area
Activate stacker cranes for coming back
go to the 0 point
read the places of the stacker crane (sensors) and actuate it when needed (actuators)
Activate the field crane for putting the goods onto the specified place at the requesting work-station
put the goods to the place
put them onto the specified places at the work-station
stop at the requesting station
go to the requesting station
Activate the field crane for delivery of the goods
deliver the goods to the requesting work-station
field crane on the out-going position
handle the goods
Activate the field crane for handling the goods
handle the box
stop at the out-going position
Activate a field crane for going to the place of the goods
go to the out-going position
field crane on 0 point
Check the places of field cranes
needed goods are on out-going places
read the barcode of the box of the goods (sensor)
goods on out-going point
Specify the position of the needed goods
Specify the position of the requesting work-station
receive the delivery of goods instruction
create pull instructions for the needed quantity of the components (Warehouse software)
read the places of the stacker crane (sensors) and actuate it when needed (actuators)

Chart B.22: Initial Concept Assembly

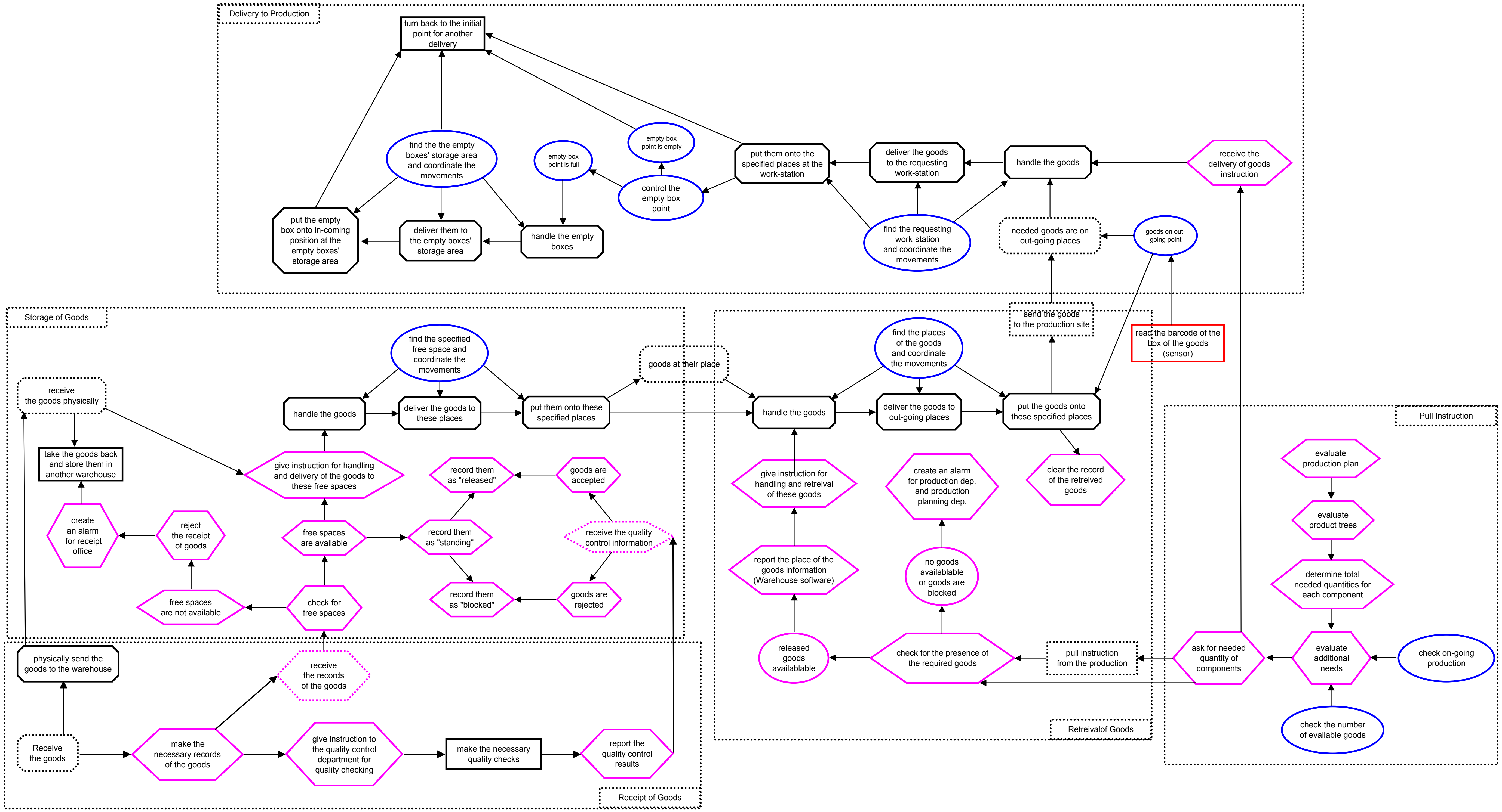
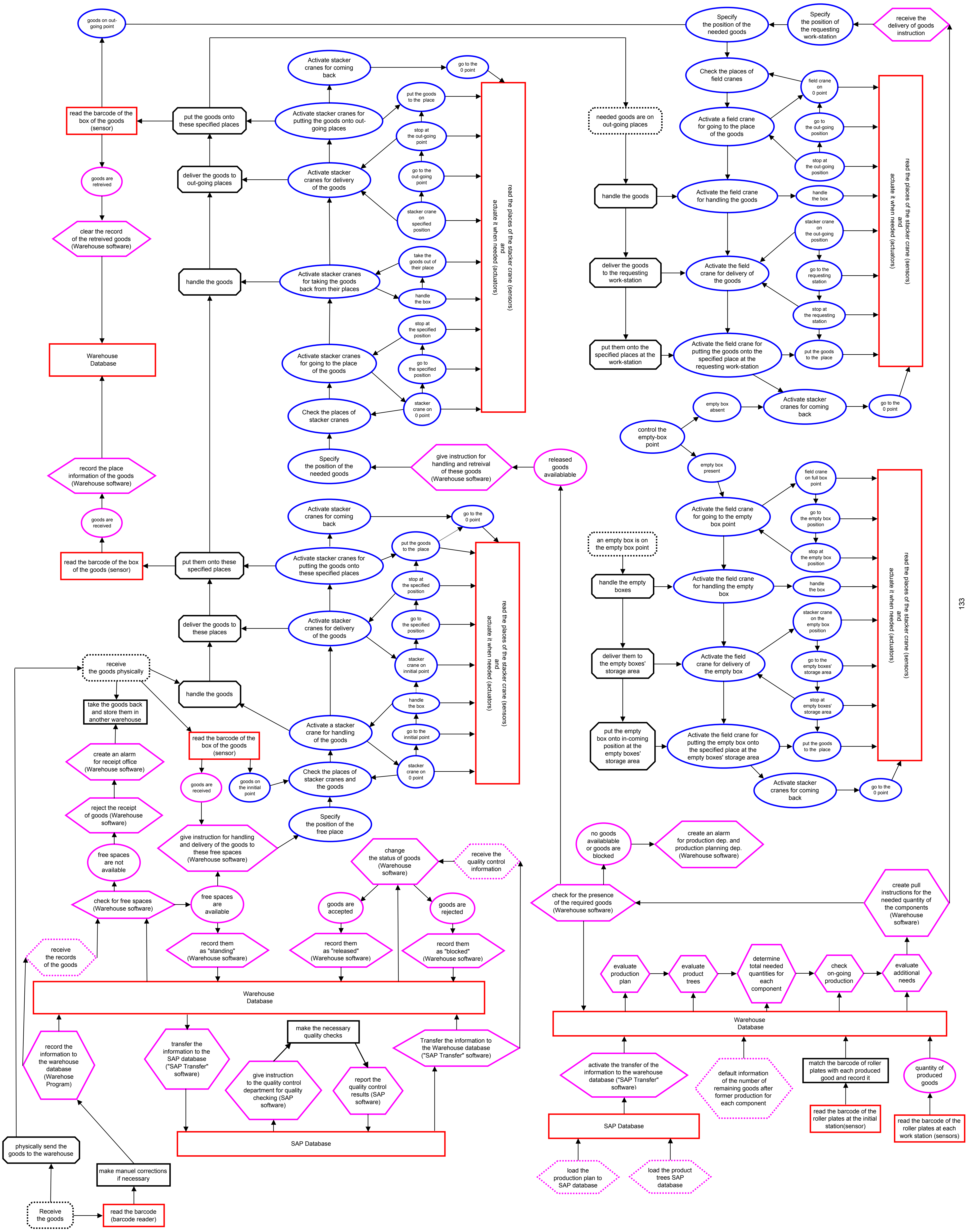


Chart B.23: Final Concept Assembly



AUTOBIOGRAPHY

My name is Murat Sevindik. I was born in Gümüşhane in 1979. I started to my primary school in Gümüşhane at Sadık Köyü İlkokulu in 1986 and completed it in Istanbul at Marmara İlköğretim Okulu in 1991. Later on, I completed my secondary school at Marmara İlköğretim Okulu in 1994. Then, I completed high school as the third ranking student at Fatin Rüştü Zorlu High School in 1997. In the same year, I have started to my university education at the Mechanical Engineering Department of Istanbul Technical University.

I entered to Preparation School of English in ITU in 1997 and started to my engineering education in 1998 at Mechanical Engineering Department. I was a double major student from 1999 to 2003 at Mechanical Engineering and Management Engineering Departments. I was graduated from Mechanical Engineering Department in 2002 as the first ranking student of the faculty and from Management Engineering Department in 2003. I started to my Master's in the same year at the Management Engineering Department.

After completing my military service in January 2004 in Ankara, I started to my first job in Arçelik AŞ. Washing Machine Plant as production planning engineer in April 2004. I still work in the same company with the same title.

Murat Sevindik

Mechanical and Management Engineer (İTÜ)

January 2007