THE INNOVATION PROCESS OF A UNIVERSAL REMOTE ACCESS DEVICE

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ABSTRACT

A small design firm faces several risks when designing a new product. One of the biggest risks is not knowing the potential demand for a product that they might want to produce and market. Small firms have limited resources and cannot afford to design products that would fail in the marketplace.

The concept of innovation refers to bringing a new product to the market successfully. Bringing a new product to the market before a competitor does so, reduces the potential risk of failure by the producer and increases their chance of successfully marketing their new product. It is difficult to assess the potential degree of innovativeness of a product before it is marketed.

The most innovative products are those that satisfy the needs and wishes of the client as closely as possible. It is therefore necessary to somehow include the wishes of the client in the design stage of a new product. This will ensure that the wishes of the client is reflected as accurately as possible in all the design stages of a product, reducing the risk that the final product will miss its target clients.

A Quality Function Deployment (QFD) process is used in the conceptual design stage of a new product to construct a user requirement statement. The closer this statement reflects the wishes of the client, the more potentially innovative a product may be. By using Multi Criteria Decision Making techniques, and especially the latest methodology in applying Thomas Saaty's Analytical Hierarchy Process, a clearer picture of design requirements may emerge. The design requirements may more closely reflect customer requirements by using techniques that have been proven to work better by other researchers.

In addition to reflecting the wishes of the client, the proper use of system engineering techniques for the new design should be implemented. Using these systems engineering techniques, a design is carried out in an organised fashion and precious resources are not wasted and the QFD techniques are facilitated.

As a case study, the evolution of a patented universal remote access device is described. The initial bad designs that lead to less innovative devices, are corrected when the wishes of the client are included in a new design. This successful design incorporates the QFD techniques described above.

UITTREKSEL

Klein produkontwerpfirmas ervaar verskeie risikos wanneer hulle 'n nuwe produk ontwerp. Een van die prominentste hiervaan is om nie die potensiële vraag na 'n produk wat hulle wil bemark te kan bepaal nie. Klein firmas het slegs beperkte hulpbronne tot hulle beskikking en kan nie bekostig dat hul produkte nie in die mark sal slaag nie.

Die konsep van Innovasie verwys daarna om 'n nuwe produk suksesvol te bemark. Om 'n nuwe produk te bemark voordat 'n mededinger dit doen verminder die potensiële risiko vir die vervaardiger om moontlik te faal as gevolg van beperkte aanvraag vir hul nuwe produk en vergroot die kans om hul nuwe produk suksesvol te bemark. Dit is moeilik om die potensiële graad van innoverendheid van 'n produk te bepaal voordat dit bemark word.

Die mees innoverendste produkte bevredig die behoeftes en wense van kliente so getrou as moontlik. Dit is dus nodig om op 'n manier die wense van 'n klient in die ontwerpsfase van 'n nuwe produk in te sluit. Dit sal daarvoor sorg dat die behoeftes van die klient so getrou as moontlik in al die ontwerpsfases van 'n produk weerspieël word en sodoende die risiko verminder dat die produk sy teikenmark kan mis.

'n Kwaliteitsfuksie-ontplooiing proses word gebruik in die konsepontwerpsfase van 'n nuwe produk om 'n gebruikersbehoeftestelling saam te stel. Hoe nader hierdie stelling die wense en behoeftes van kliente weerspiëel, hoe groter is die kans dat dit die potensiële innoverhentheid van die produk kan verhoog. Deur van multi-kriteria besluitnemingstegnieke, en veral deur die nuutste metodlogie van Thomas Saaty se analitiese hierargie proses gebruik te maak, kan daar moontlik 'n beter geheelbeeld van die ontwerpsbehoeftes tevoorskyn kom. Die ontwerpsbehoeftes mag dalk die behoeftes van die klient beter weerspiëel deur van tegnieke gebruik te maak wat navorsers al bewys het dat dit goed werk.

Behalwe vir tegnieke om die behoeftes van kliente in die ontwerp van die produk in te sluit, moet die behoorlike toepassing van stelselingenieurswesetegnieke ingespan word vir enige nuwe ontwerp. Deur van hierdie tegnieke gebruik te maak geskied die ontwerpsporses op 'n georganiseerde manier sodat skaars hulpbronne nie vermors word nie. Hierdie stelselingenieurswese tegnieke fasiliteer ook die implementering van kwaliteitsfuksie-ontplooiing tegnieke.

'n Gevallestudie word gedoen om die evolusie van 'n gepatenteerde universiële afstandstoegangtoestel te beskryf. Die aanvanklike slegte ontwerpsbesluite wat gelei het tot produkte wat minder innoverend is, word gekkorigeer wanneer die wense van kliente ingesluit word in 'n nuwe ontwerp. Hierdie ontwerp maak gebruik van die kwaliteitsfuksie-ontplooiing tegnieke waarna hierbo verwys is.

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AHP	Analytical Hierarchy Process
AI_j	Absolute importance rating of DR_j, j=1,..,n
CI	Consistency Index
COS	Cost (customer requirement)
CR	Customer Requirement
DDP	Design Dependant Parameters
DIP	Dual In-line Package
DR	Design Requirement
EOU	Ease of Use (customer requirement)
HOQ	House of Quality
IND	Independence (modularity) (customer requirement)
MCDM	Multi Criteria Decision Making
PWC	Pairwise comparison matrix
QFD	Quality Function Deployment
R&D	Research and development
RF	Radio Frequency
RI	Random Index (Random Consistency)
RI_j	Relative importance rating of DR_j, j=1,..,n
SAF	Safety (customer requirement)
SEC	Security (customer requirement)
SMART	Simple Multi-Attribute Rating Technique
SUP	After sales service and support (customer requirement)
TPM	Technical Performance Measures
TQM	Total Quality Management
URS	User Requirement Statement

Two design iterations followed the conceptual design phase. The first iteration was done by a small design firm first contracted by the entrepreneur, and the second was done by ourselves. The result of the initial design was a device that was functionally similar to popular keyring versions of remote access devices that are available in the market – this design was initiated by means of "brain storming" in isolation from the end-user. The second design was a significant improvement on the first by using input from the end-user and installers as opposed to the first approach, although valuable information followed from the initial design since the first device was shown to the market in order to gain market feedback.

The differences between the first vehicle-fitted remote access device and the current handheld remote access devices were that the vehicle-fitted device:

- used the battery of the vehicle that it was fitted to,
- used the normally open switch of the bright headlamp circuit to activate the device, and
- was housed in a plastic casing that was resistant to the temperatures and fluids that are encountered in the engine compartment of a motor vehicle.

Although the initial device (from the first design iteration) was accepted by the market, some major difficulties remained from a user perspective. It is a fact that different access control installers use different types of access control devices. The first device did not provide universal access to all different types of access points and had to be replaced every time another type of access point had to be added. This caused logistical problems for remote access service provider companies as well as the end user since, for each access point, another device had to be installed (this also caused installation problems).

The result of not utilizing the end-user's input from the onset (the contribution of the first design as input to the second design is acknowledged, however), was that the first design was not as innovative as it could have been because it did not provide all of the functions for which the user wished.

The patent holder needed to capture a larger slice of the market by maximizing the potential of the patent. In order to achieve the new design for his patent, we had to:

- research and define an innovation process to design a remote access device in order to minimize the risk taken by the entrepreneur, thus providing a framework for innovation that aided the decision-making process because the entrepreneur could then take informed decisions using this framework;
- because of limited resources available for product Research and Development (R&D), a device was required that reflected the requirements of the end user more accurately from the onset of the design (with as few as possible design iterations) – this was achieved following a quality design process;
- a vehicle-fitted remote access device for the entrepreneur in the form of an end product was actually developed and industrialized;
- the finally achieved technical results were verified against the initially available technical characteristics. In addition, questionnaires were issued to all available installers (this was not the main objective of the study, but had to be done in order to provide closure to marketing).

From the above discussion, we see that the ***process of transforming*** the ***user's requirements*** to ***technical requirements*** is important and therefore forms an integral part of this research. Marketing-related aspects such as interviews with end-users did not form the main focus of this study, although results were achieved by using a questionnaire sent to all available installers during the final stages of this research. Therefore, it was not the main objective of this study to gather marketing information, but rather to use the obtained marketing information (as obtained from the entrepreneur) as input to the transformation process called Quality Function Deployment (QFD), in order to achieve a technically successful result. The technical result from a new design is measured and verified against the initial technical design, and the goal of an improved technical design is achieved when the new design outperforms the initial design on technical measures. The verification of innovativeness that were obtained from installers were considered to be a sufficient but not necessary result of this work.

This chapter provides a summary of the results of a literature study on innovation, as well as the technical aspects of the transformation process i.e. the technical side of QFD.

1.1 Techniques to design innovative devices

In this sub-section, innovation, as a framework for decision making and benchmarking, is studied. When marketing a product, the concept of innovation (defined in section 1.1.1.1) comes into play.

If the level of innovation for a potential product could be measured by using the wishes of potential clients as input to determine the most critical high level design requirements, a design process can be focused on the important part of the product namely to meet the wishes of the client and to reference a product relative to existing products.

Techniques are required to transform client input requirements into a quality concept design. Organised systems engineering techniques are available to efficiently design a product. The most important part of a design is to determine what features to include in a design to make it potentially desirable to the market. In addition, techniques are required to translate possible measures of quality into design parameters of a product.

1.1.1 Aspects regarding the measurement of innovation

A direct relationship exists between innovation and success in business. Innovation is necessary to stay competitive. It is important to either manufacture popular products at lower cost than the competition or to create new and desirable versions of a product for which the market is willing to pay more. The best opportunity would lie with the ability to turn a new idea for a product into a commercial success, i.e. to create a new market.

If the availability and magnitude of R&D funding is a limiting factor, the innovation of wholly new products is limited. In such a case it might be more appropriate to functionally enhance an existing product by adding desirable features (incremental innovation).

It was necessary to study the process of innovation and to measure the success of this process for this study. For this research, the measurement of innovativeness is important insofar it may be used to indicate the potential relative market success of the final product.

1.1.1.1 A Definition of innovation

After conducting a literature study, Neely and Hii [14], concluded that innovation is the successful exploitation of ideas. It may be restated in business terms that it is the making of profit by the marketing of a new device or service. Innovation is not to be confused with coming up with a new idea for a device or product. It must be an idea that is taken to the marketplace and it must make a profit.

Innovation is not mere invention. An invention that is not taken to the marketplace and that is only remaining as a laboratory experiment is not referred to as an innovation. The degree of technological advancement and the scale of the impact on the market are important when measuring innovativeness (the degree to which the innovation has an impact on new technology or new markets.)

Innovation also refers to the marketing of a product or concept that contains new technology. In the definition above it is stated that the marketed product has to be a success. This is also one of the main reasons to study the innovation process to establish the key parts that are important in terms of market success.

The innovation process refers to the methods used in coming up with new ideas and taking these ideas to the market. This study is for the most part concerned with looking at the innovation process from the company or design firm's perspective.

Innovativeness of a person or firm refers to the degree that the person or firm is willing to innovate before others will be doing so. In this case the term, innovativeness, is used to describe attributes of a person or firm with regard to innovation.

Innovativeness of a product refers to a measurement of the degree of "newness" of a product according to Garcia and Calantone [5]. Innovativeness is a relative term and has to be treated as such. A radical innovation to one firm may be a gradual one for another. This study is mostly concerned with the measurement of innovativeness of a product rather than of a person or company.

A person or organization's capacity to innovate or its innovative capacity refers to the capability to be able to bring new ideas successfully to the marketplace. Neely et al. [14] have indicated that firms with a higher innovative capacity indeed create products that are more successful in the marketplace.

1.1.1.1.1 The multidimensional nature of innovation

Innovation may refer to three factors:

- product innovation refers to the successful introduction into the market of a new product,
- process innovation refers to the successful introduction of a new design and manufacturing processes that are used to produce products at more economical levels,
- and organizational innovation refers to the environment in which innovation takes place. A business and individuals that are geared to be more innovative will be the backbone of the innovative process. It also refers to the making use of the best-educated personnel and the latest affordable technologies.

In terms of innovation, product innovation will be reviewed in this study. The technological changes made when augmenting the functionality of a product are described as well as the impact the product has on a market. The impact of the addition of technology to enhance a product must be weighted against the impact this technology has on the user requirements deemed to be the most important.

1.1.1.1.2 Degree of innovativeness

The process of innovation may be a gradual one or a revolutionary one. The ideal situation would involve a brilliant idea that does not cost much in the form of input cost to develop. It is obviously counter-productive (negative innovation) to spend huge amounts of capital on developing new technologies and the profits do not even recuperate the invested capital.

Previous studies [5] have shown that confusion exists in how a degree of innovativeness is defined. It is important to remember that the degree of innovativeness is a qualitative, subjective term. The perspective from which this degree is viewed is important. From one perspective an innovation may seem radical, from another that same innovation may seem incremental or gradual. What is common in most studies trying to measure innovativeness is that a radical innovation is characterised by:

- a discontinuity occurs in the technology that is used or
- a discontinuity occurs in the marketplace.

The study by Garcia and Calantone [5] suggested that the classification of the degree of innovativeness should be standardised so that future research could be simplified. A major problem in the past is that researchers used different language terms to describe similar degrees of innovativeness. Table 1.1 gives a short overview of a recommended classification system for degrees of innovativeness from [5].

As seen in the table, a radical innovation is one that represents a huge jump in both technology and market organisation. The personal computer (PC) is an example of a radical innovation. This innovation took computers into the home for everyone to use, not just scientists and businessmen.

A really new innovation refers to the fact that either the market or the new technology was viewed as radically new but not both. The compact disc (CD) is an example of a really new technology, creating the popular music CD. The music market though, was established through the Long Playing vinyl record (LP) technology.

Discontinuity				**Incremental innovation**	**Really new innovation**	**Radical innovation**
Technology		**Market**				
Incremental	**Radical**	**Incremental**	**Radical**			
	X		X			X
X			X		X	
	X	X			X	
	X				X	
			X		X	
X		X		X		
X				X		
		X		X		

Table 1.1 Classification of the degree of innovativeness as suggested by [5]

The original version of the vehicle fitted remote access device (as opposed to handheld devices) may be classified as an incremental innovation from the design firm's perspective. This is because the market and technological discontinuity was minor. The same market that utilizes existing remote access devices also uses the vehicle fitted remote access device. What distinguishes the vehicle-fitted device from other products in the marketplace, is the functionality that the device offers as viewed from a user's perspective. This functionality change was enabled by the reconfiguration and innovative application of existing technologies that have become available to the market at a reduction in price.

Further improvements on the remote access device evolved from earlier versions through the addition of new ideas and some newly available technology. Remote access is not a completely new idea, but additional functionality and newly available technological capacity should contribute to the design of a new product.

If a small design firm is short of resources to spend on R&D to come up with radical or really new innovations, attention should be paid to incremental innovations. A process should be undertaken to enhance a product by adding functionality that would be attractive to potential customers in the marketplace.

1.1.1.2 Measurement of innovativeness

It is difficult to measure innovation because innovation as a concept is multidimensional in nature. In most studies, innovation is measured indirectly by recording innovative activities that have taken place. Examples of these are:

a) the number of new innovations Research and Development (R&D) turned out,
b) the amount of money that a company spent on R&D,
c) and the number of patents registered by a person or company (inventions).

Patents are important because it means that only the patent holder may commercially exploit a new idea. Only new ideas may be patented. This reduces the risk for a potential investor, knowing that only the company and product that is invested in, may exploit the new idea.

Innovative activities b and c refer to innovative capacity rather than innovation. For an innovation to be regarded as such, the new product resulting from an R&D project must be marketed.

If the success of innovation is measurable, a potential investor may be persuaded to invest in a company in which the success rate is above average. This will complete a good circle of innovation by allowing the company that has attracted investment to spend more of the funds on Research and Development.

1.1.1.2.1 Research and development expenses

Research and development expenses as measurement of innovativeness is mostly used in a macro (broad market) sense when surveying producers to decide who are more innovative. A company that spends more money on R&D is expected to introduce more new (innovative) products to the market.

From a micro (development firm) perspective, innovation must be measured in other ways. The new technologies used must have an impact on the sales of the firm in the market. This is an iterative trial-and-error process. In most cases there is only one chance to develop a new and innovative product before funds become limited.

There should also be a measurement of the potential innovativeness or innovative potential of a product. This may be obtained from the process of deciding which technologies to use when designing the product. By predicting the innovativeness of a product beforehand, R&D expenses may be limited because potentially expensive redesigns are limited and risks are manageable.

1.1.1.2.2 Areas of innovation

In the above frame of reference, the final vehicle-fitted remote access device described in this dissertation is an example of incremental innovation largely due to:

- the change in functionality, aided by affordable lower-end technologies (processors and RF devices) to move away from handheld devices and to use the vehicle's light switch and battery,

- utilization of firmware to implement increased functionality as opposed to using a remote access device for each access point, and
- self-learning (intelligence) in the form of automated access code configuration. The final design implements a code grabbing device to record, analyse, and re-program the vehicle-fitted device for each new access point.

As such, the final design is in no way radical with regards to the previous design or to handheld remote access transmitters, neither does it require the market infrastructure to change. The major changes compared to the handheld devices are in terms of functionality. Now the user is able to access many types of different systems that use different codes with one device. The access gate at the end-user's place of work may use a different type of code than the one at home. Another functional increment is the installation of the device in a vehicle. A device learns the code form a handheld remote access device and programmes a transmitter device that is fitted into the motor vehicle would ensure that less skill is required at the point of installation (as opposed to setting switches to select a code). The lower cost of installation and faster installation could make the device more attractive to a potential customer.

With this type of innovation in mind, it is most important to also include the priorities of the client / end-user in the measurement of innovation. If the wishes of the client are included in the final product, it is more likely that the product may turn out to be a success in the marketplace due to increased "buy-in".

A User Requirement Statement (URS) would be an ideal place to assess the potential market success of a product. This is where clients, together with the design team, decide how the product should work and the specific functions the product must be able to perform. This is why we had clients participate in the conceptual design phase in order to reduce the number of costly detail design iterations.

As mentioned, the potential innovativeness of a product from the point of view of a technology development firm is important to this study. A firm must decide what is important to be able to achieve its goals and use this information when designing future products. Not all design firms have the resources available to design and build products and test the finished product in the marketplace.

The macro impact of the product on the marketplace and the classification of the degree of innovativeness may be the study of a market researcher comparing the firm to other firms. Although this may be important, it is more important to determine potential innovativeness of a product and to optimise the decision of which technologies to use when designing a product.

1.1.1.2.3 Using the User Requirement Statement as a reference for measuring innovativeness

From the previous discussion it is clear that both the potential market and potential technological discontinuities of the proposed product are incremental as viewed from a broad perspective. The vehicle fitted remote access device is yet another way to implement a remote controlled switch. From the design firm's perspective this new product may increase market share significantly or create spin-off markets for products that may also make use the improved technology.

The design firm has to establish a method of measurement to calculate the impact of a certain added technology, which introduces new functionality to the product, upon the market. When pushing new innovations into the market, it is difficult to guess whether the product would be successful. Market need cannot be used to describe a potential market because the market does not know all the needs that a new innovation might fulfil [15]. Technological innovations must also cater for the wishes of the user and not just for the needs of the user.

Further difficulties arise when the client of the designed product and the end user are not the same. Such a client requests that a design firm develops a new device that conforms to his or her specifications. Such a product may only be successful in the marketplace if the client has established beforehand that there is a need in the end-user marketplace for this product. From the design firm's perspective, the product is successful if it complies with its design specifications as requested by the client. When designing a new product, it may be necessary for all parties involved (client and design team in this case) to cooperate with the single goal of satisfying the wishes and needs of the end user.

The final remote access device that is treated in this study is not an example of a major technology push. It was designed to the requirement of a client to be manufactured and sold by the client. The use of newly available technology in the design was suggested to reduce manufacturing cost.

A system engineering approach should be used to design the remote access device. The first step is to compile a User Requirement Statement (URS). This statement is compiled together with a value system of the client indicating the relative importance of the various Quality Functions (specific qualitative user requirements that are difficult to measure directly). The URS, in most cases, is the only document reflecting the final wishes of the client. The decisions about which technologies to use are (as in the case study) based upon these wishes.

Quality Function Deployment (QFD) is a method whereby the wishes of the client are reflected in the final product. The results of a QFD process aid in deciding upon measurable system level specifications during the preliminary design phase. The resulting outputs serve as inputs to later stages of QFD involving subsystem level design, the design of the manufacturing and maintenance concepts, etc. Obtaining the inputs to the QFD process is a marketing function, whereas the transformation of the user's wishes to a marketable product is a joint function performed by both marketing and technical persons. The outputs of the QFD process are, in turn, the inputs to the ensuing systems engineering function (i.e. the derivation of detail requirements and specifications from the outputs of the QFD process).

The first technical step (following the marketing steps) of a QFD is where design requirements are prioritised based on customer requirements. In the system engineering approach, the results obtained from the House of Quality (HOQ) are used to resolve the high level functional analysis. The QFD process as well as the HOQ construct and its use are discussed in chapter 3.

User requirements and possible technologies to be used form a technology space in later stages of the QFD process. This space may be represented in the form of a two dimensional matrix similar to the HOQ with the design requirements and technological solutions as inputs.

The User Requirement Statement will also be used as a reference point for measuring the innovativeness of the product from the design firm's own perspective. A metric or indicator shall be obtained from the QFD reflecting the optimum design such that the optimum design will be the design that will satisfy the customer the most. According to Neely and Hii [14], whilst agreeing that innovation is difficult to measure, a top priority should be to ensure customer satisfaction.

Deciding upon new technology to be used is driven by the user requirement. The designer plays an important role when deciding on a new technology. The correct technology must be applied to best reflect the wishes of the client\user as well as keeping costs as low as possible, reducing the price of the marketed product. This will increase profit margins and reduce risk of commercial failure to a degree.

Quality Functional Deployment is one of the important aspects that constitutes Total Quality Management (TQM). Prajogo and Sohal [17] analysed and provided available literature regarding the Relationship between TQM and innovation.

Several of the studies (as described in a literature review by Prajogo and Sohal [17]) found that applying TQM techniques enhance both product and process innovativeness. This is mostly the case when referring to incremental innovativeness. Incremental improvements and functional enhancements lead to the availability of improved products. An important result is that indeed, the detail development carried out later during the development is, effectively, driven by the client.

Various other studies (as from [17]) found that TQM techniques could have a detrimental effect on innovativeness. This is usually the case when referring to really new or radical innovation. This detrimental effect occurs because the TQM process, and therefore the QFD process, focuses on incremental improvements of a product or process over its predecessors. The potential client is unaware of new technologies that may become available in the future and therefore does not know what the potential use of a product might be. It would be difficult to use customer requirements as a measurement of potential innovativeness.

1.1.1.2.4 Failed innovation

Failed innovation refers to spending a lot of money and other resources in developing new technologies and products, but not marketing these products. In a market related business, failed or negative innovation must be controlled more strictly. Market success in terms of profits made must be measured as a final measure of innovativeness. Obviously the profits made must be measured in terms of both the expectation of the technology firm and expectations from investors in the firm.

1.1.1.3 The relationship between innovativeness and improved market penetration

The measurement of innovativeness involves the measurement of the improvement in technology or technological performance of a product as well as its success in the marketplace.

Marketing is more or less defined by Strydom et al. [18] as:

"A number of managerial tasks together with decisions that have to be made, to seize opportunities and counter threats from competitors with the goal of satisfying all the requirements (needs and wants) of the customer."

They also add that these steps must be taken to meet the objectives of the organisation marketing the product and the objectives of the customer in a socially responsible way. As stated earlier, the objectives of a company are a sustainable profit and not just a short term profit strategy.

When making decisions with regard to marketing, four variables are considered. They are referred to as the market instruments or the four P's of marketing namely:

- decisions about the Product itself,
- the Price that the product should sell for,
- the Place where the product is sold,
- and the Promotion of the product.

It is clear from the literature that marketing a product should be client orientated. The needs of the client should be the main focus, supporting the approach of quality design. A company following a production orientated marketing strategy mostly focuses on manufacturing the best product they are able to design and make. This approach increases the risk of failure because the product might not sell because the client does not really need the product, even though the company manufacturing it are experts in their field.

If, as in the definition of innovation adopted in this study, the marketing of the product must be a success, the newness component of a product implies the implementation of new technology that is useful to the customer.

The framework for marketing shows that the link between marketing and innovation lies with the product and its cost-effectiveness. When the end-user assists with the definition of the product, as is the case with quality design, then the marketing function of an organization will be linked to the development function through a process such as QFD. Therefore, following a QFD process correctly and using reliable input information to the process, should result in increased market potential.

There are significant advantages to developing a device that is innovative in certain areas:

- the risk of market failure is reduced because the product will be better than that of the competition because the client appreciates the improvements most,
- the potential exist for bigger profit margins,
- and capital is spent more wisely on R&D funding as resources are not wasted and are available for the development of new products leading to more profits.

1.1.1.4 Summary of literature review regarding innovation

Innovation refers to the marketing of a new or enhanced product. The innovativeness of a product is difficult to measure but client satisfaction plays a significant role in this measurement. Quality Function Deployment is used in industry to translate customer requirements into design specifications at the preliminary stages of a design. The more accurately a QFD process can reflect customer requirements in the final product, the better the innovativeness of the product. The potential innovativeness of a product may be measured by how closely the design would conform to the benchmark requirement given by the HOQ construct of the QFD process.

1.1.2 Quality product design

One of the common problems with designing a new product is that it is sometimes not done systematically or in an organised manner [4]. It requires extra time and effort to do a systematic design and systematic design is therefore often neglected. If a haphazard approach is followed, resources are wasted and the design might not be optimal.

A systematic design approach will help the designer to focus on the goal of the design. The designer or design team should systematically translate requirements to solutions by selecting appropriate technologies. Solving the problem and satisfying the wishes of the customer should be the main focus of a design. The choice of which technology to use is usually a trade-off between performance and financial resources to implement all aspects of a technology including the intellectual resources to implement these technologies.

1.1.2.1 System engineering approach

Designing even a small system requires a clear plan. A design must be approached in an organised fashion. Fabrycky and Blanchard [4] describe such a process for engineering systems in general. This process is applied (and adapted) in this work for the development of a small electronic device that include both hardware and software.

From past experience in the design of systems involving microcontroller devices, the design time is speeded up significantly if a step-by-step clear design plan was followed. The product designed by using these methods often works the first time and actually performs the functions it was intended for.

1.1.2.1.1 A brief summary of the design process

The system engineering process consists of a number of stages. The main outline of the approach followed is illustrated in figure 1.2. Shown in the development and production cycle is the place where QFD will be most effective, namely in the requirements phase.

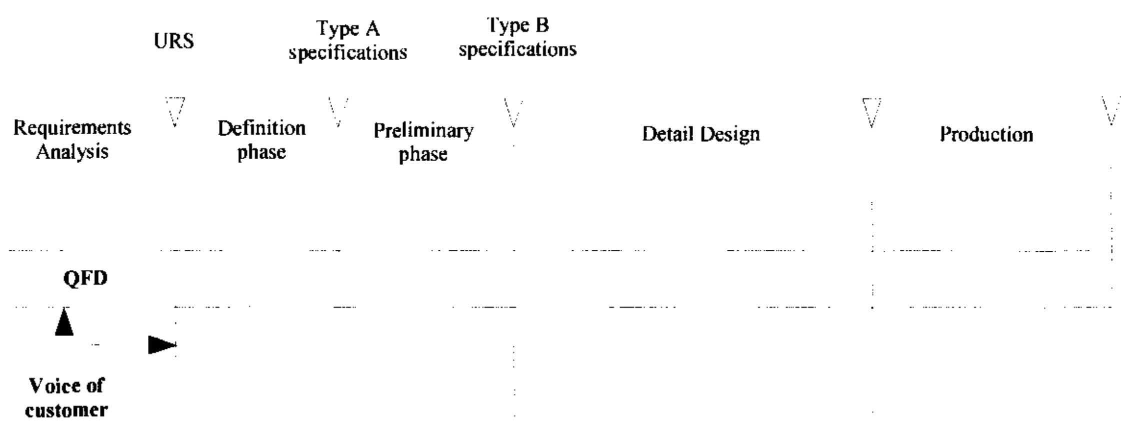

Figure 1.2 Design milestones

One should bear in mind that every phase has a number of secondary steps involved. Feedback is important inside and between each and all of these stages. At any stage the design may be reviewed and changes may be made. Design reviews are also necessary at the end of each stage.

The production, maintenance and disposal of a product should be taken into account when designing a new system. This study is mostly concerned with the early stages of the design process. The first stage of any design is the conceptual design. This involves the Requirements Analysis phase where the requirements of the client is determined and feasibility studies are conducted to see if the problem can be solved with available resources and technology. A system functional analysis must also be conducted. The functions must be described independently from the technologies that will be used to fulfil these functions.

The steps selected to complete the development of the vehicle-fitted remote access device are the steps from the systems engineering process most crucial to any design. These are:

- Requirements analysis,
- Functional analysis,
- Allocation of requirements,
- Trade-off analyses,
- System level specifications,
- Preliminary Design,
- Detail Design.

In the worst case scenario, no organised system engineering design approach is followed at all when designing a new product. Taking this approach increases the risk of failure of a project. The complete product life cycle should be taken into account when designing a product. This includes the production, maintenance and disposal of the project. This is illustrated in figure 1.3.

Acquisition phase				Use Phase
Requirement	Concept	Detail	Production	Use and maintenance
Develop support plan				Technical Support
Plan production method			Produce	Upgrade production techniques

Figure 1.3 Product life-cycle. Adapted from Fabrycky and Blanchard [4], p.19

Although the detail design was performed and verified, this study focuses more on the quality design aspects of product development. There are, however, a few necessary steps at the beginning of a design that must be taken into account to ensure that the design will be on track and that unnecessary cost, time and risk will not be incurred. During these initial stages the potential innovativeness of the final product must be maximised.

A good conceptual design is required for all designs. This involves the proper analysis of the user requirements, a good system level (operational) functional analysis and the establishment of design requirements.

A compelling reason to follow a system engineering approach to design is that QFD techniques will be used to establish Design Requirements (DR's) from Customer Requirements (CR's). Govers [6] remarks that to apply QFD techniques to improve any (design) process, a system engineering approach needs to be followed when conducting the (design) process.

1.1.2.1.2 Commonly neglected areas of design

The most common factor of neglect is not to follow an organised systems design approach. Specialised techniques to perform the steps in a design process may then be explored and developed. In most of the cases of a weak design, a technology is picked and a development is undertaken using this technology. *What should happen, according to [4], is that the **true** problem should be defined.* How could a product be designed to solve a problem if the problem that has to be solved is misunderstood?

The initial stages of a good approach to systems engineering revolves around the transformation of client input into measurable design properties. Aspects of design that are often neglected is discussed by Fabrycky and Blanchard [4] and includes the steps of conceptual and preliminary design, which are:

- requirement analysis,
- functional analysis, and
- requirements allocation.

The requirements analysis at the beginning of the systems engineering process is usually neglected which leads to a poor reflection of customer needs and wants. The House of Quality (HOQ) of the Quality Function Deployment (QFD) process is of great assistance as a decision-making tool when the importance of design requirements are determined.

A design gets increasingly difficult to change in terms of cost and time the later the design progresses [4]. The voice of the customer must be represented as accurately as possible when the user requirement statement is constructed. QFD is used to determine the importance of design requirements (DR's) given the requirements of the customer. If the requirements of the customer are determined to a greater degree of certainty, the functions that the device has to fulfil are more accurately determined.

Using QFD, the voice of the customer will be represented in every aspect of the design from the design requirements to the choice of technologies used. The risk of failure is minimised and potential incremental innovation is maximised. The QFD process thus also assists in the requirements analysis task by providing a method for making decisions. Just as any multiple criteria decision making tool, the QFD process can not make a decision, but it will definitely help the design team to take every factor that influences the design into account and place it in the correct proportional perspective.

A mistake that is made often, is to choose a technology that will be used in a design before the requirements of the client are taken into account. Often expensive components may be included in a device to perform functions that may not be required.

A functional analysis is represented in the form of a functional flow block diagram. An example of a functional flow diagram is shown in figure 3.3 (see page 61). A system level functional block diagram does not include subsystem functions. Subsystem functions will be included in the detail design stages of the product as and when needed.

A functional analysis is an essential part of the QFD process. It will give a compact overview of all the functions the product must fulfil as requested by the client. At some stage these functions will be grouped together into logical units that execute the functions. A user interface display, for example, may be implemented with an array of lights instead of an expensive liquid crystal display.

Resources must be allocated to functions after the system level functional analysis has taken place. The QFD process will also play an important role at this stage of the design. Prioritised design requirements are used to determine which technical solutions will please the customer the most.

If budget constraints become influential on the design, the expensive component that would have the least impact on the requirements of the user may be discarded and the technology that fulfils most of the user requirement may be kept.

1.1.2.1.3 Preliminary and Detail Design

At the preliminary design stage a more detailed functional analysis is carried out. This analysis will include all of the subsystems. The resource allocation process is carried out again, but this time on subsystem level. The next HOQ analysis may be conducted with the design requirements from the previous HOQ as inputs and prioritised technology requirements as the output. Trade-off studies may be carried out and Engineering Development Models (EDM's) may be constructed for this purpose and to validate certain conceptual designs.

Interfaces between subsystems must be established carefully so that subsystems could be easily integrated when the detail design is concluded. Software and hardware developed for EDM's may be used in the detail design if they were proved successful. If software was involved and the software included well-designed individual software modules, these modules could easily be added to the detail design.

The detail design will include activities such as

- designing electrical circuits,
- decision on components and sizes,
- writing software if an embedded computer is involved,
- laying out circuit boards,
- and the physical specifications of the housing of the device.

A system engineering approach is especially useful with the complexities of designing a system that includes an embedded microprocessor. Ball [2] highlights the complexities of a design involving a microprocessor. The type of software that may be written for a specific microprocessor depends closely on the hardware functionalities of the microprocessor such as:

- processor type (CISC or RISC),
- clock speed,
- interface type(s),
- amount of program and data memory,
- support tools and requirements.

The systems engineering approach is particularly useful to describe exactly what functions must be carried out. Knowing the precise software requirements of a system would facilitate trade off decisions that a design team must take to decide which is the most inexpensive microprocessor that would fulfil these software requirements.

Both the preliminary and detail designs follow certain steps. It is important to remember that design reviews and feedback are also part of these stages of the design.

1.1.2.1.4 Quality Function Deployment (QFD)

According to Park and Kim [16], the Quality Function Deployment (QFD) process was used first by the Japanese firm, Mitsubishi, in the early 1970's in one of their factories in the city of Kobe. It was only introduced to the so-called Western countries in the 1980's where the influence of an engineer was substantial in the design process. The idea of QFD is to improve products by taking account the wishes of the customer.

A QFD chart is a matrix where the left side is reserved for listing the requirements (WHAT's) and the top is reserved for the Design requirements (HOW's). The influence of each requirement on each design requirement is stated within the matrix. On the lower side of the matrix a metric value is given to represent a target for the design requirement. The relative importance of the requirements should also be taken into account. The use of a measurable value is important at this stage. Figure 1.4 shows a QFD chart.

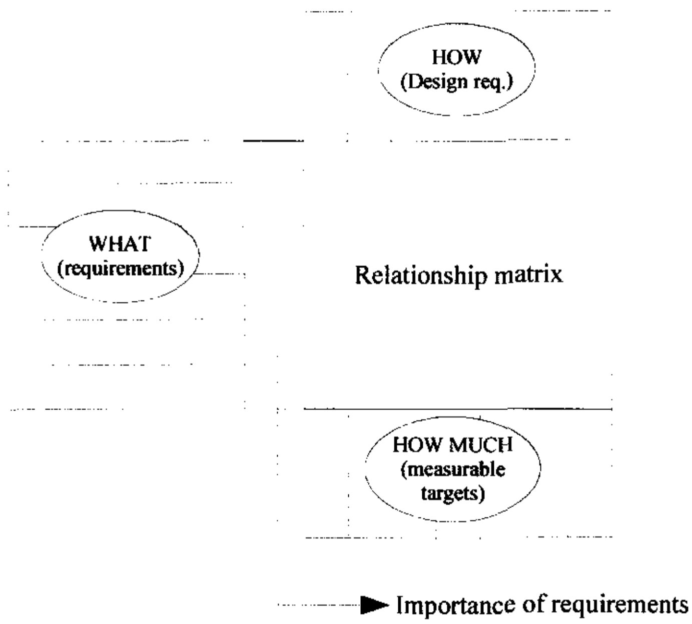

Figure 1.4 QFD structure as described by Govers [6]

A QFD chart is drawn up for each of the design stages. The design requirements at the top, as output of a previous design stage, are used as the requirements input on the left of the next QFD matrix in the following stage. The first stage involves the customer requirements as the WHAT's and the concept design requirements as the HOW's. The second stage involves the concept design requirements as the WHAT's and the product detail design requirements as the HOW's. The third stage involves the product detail design and the process design. A possible fourth stage includes the process design and the manufacturing operations.

This study is not so much concerned with the latter two stages of the design. The wishes of the customer might, or might not have a large impact on the process design and manufacturing operations. Support and maintenance, however, do play a major part in customer satisfaction and were considered in the initial stages as customer requirements.

1.1.2.2 Architecture of a House of Quality (HOQ) Matrix

An example of a House of Quality is given in figure 1.5. Information must be sourced in a certain logical order that would facilitate better decision making. A short description will be given as to what information should be collected for each section of the QFD construct.

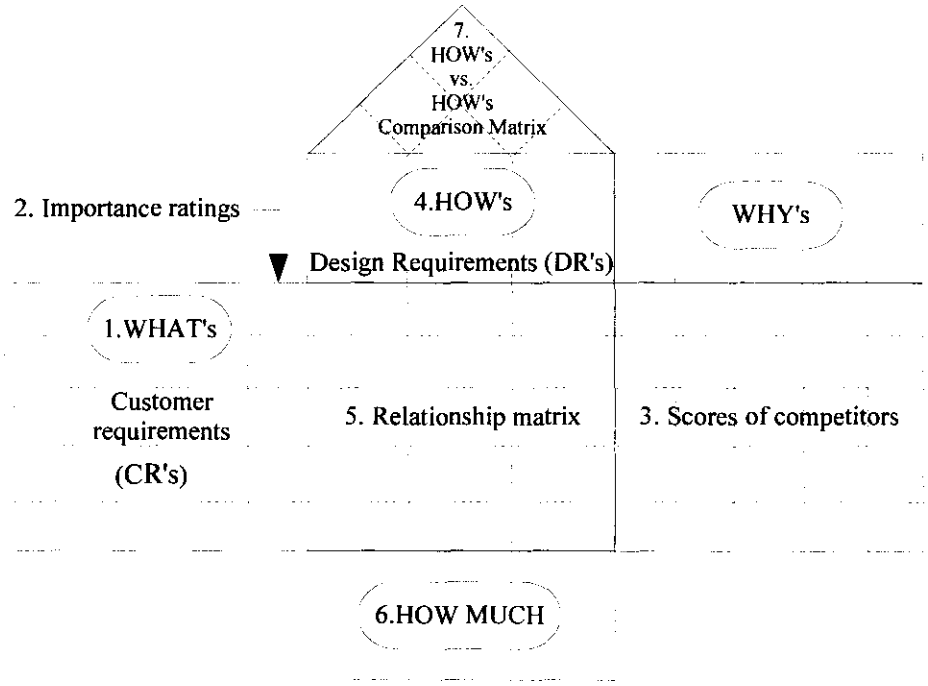

Figure 1.5 House of quality (HOQ) construct. The sequence of thought is indicated with increasing numbers

1.1.2.2.1 Customer Requirements (CR's)

The customer requirements are specified on the left of a HOQ. They should be understood by the client and not include technical terms that are not comprehensible to a non-engineering person. A good indication to a designer of whether the correct CR's were identified, are that these CR's could be easily used in a brochure that describes the features of the new product to the customer.

A function tree may be used to describe a CR in more detail. Figure 1.6 describes a 2 level functional tree that describes, for example, the "Easy to operate" customer requirement.

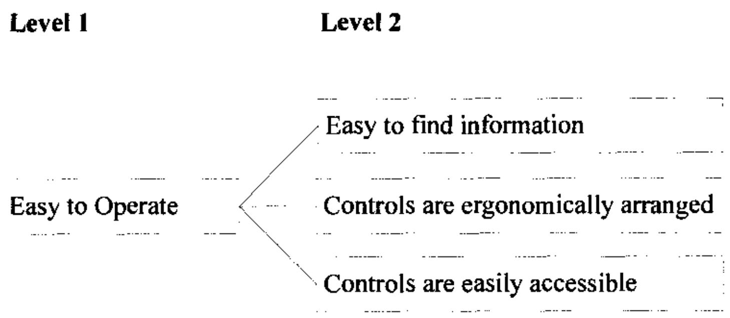

Figure 1.6 Functional tree

1.1.2.2.2 Importance rating of Customer Requirements

The requirements should be given an importance rating to indicate relative importance. The importance ratings should be normalised so that they add up to 1 so that the relative degree of the importance of CR's are measured. A higher rating will weigh more towards influencing a particular design requirement than a lower rating.

1.1.2.2.3 Competitive benchmarking

Competitive technologies as well as previous models are tested against the customer requirements. This is where the shortcomings of a current product may be measured with regard to the competition. This is also a method of identifying design requirements to address these problems.

The competitive benchmarking section is at the right side of the QFD. It is presented in the form of a graph with a scale of 1 to 5 (from poor to very good). Each of the competitors are rated in terms of a CR and given a score between one and 5. Every competitor is represented by a symbol. All the symbols of a competitor may be connected to form a graph. An example of a comparison is given in figure 3.2 (see page 51).

It can easily be seen where there is potential to satisfy a customer even more. A product that fulfils the wishes of a customer to a greater extent might be potentially more innovative. New design requirements may be identified if the competition is ahead of the design firm. The specification level of the DR's might also be increased.

1.1.2.2.4 The Design Requirements (DR's)

The design requirements are the measurable technical parameters that define a design. The relative importance of these measures will be decided based on the requirements of the customer. The DR's are represented in the "ceiling" of the HOQ.

Experience is a necessity when identifying DR's. If technical parameters are required that could not possibly be met given available knowledge and resources, they should not be included in the product.

1.1.2.2.5 Relationships between CR's and DR's (relationship matrix)

The influence of a design requirement on a customer requirement is indicated in the matrix. Traditionally a 9-3-1 technique was used and was usually represented by a symbol. A 9 would indicate a strong relationship, 3 a medium one and 1 a weak relationship. The reason is so that a strong relationship would stand out and a situation will not arise where a number of DR's have similar ratings would make comparisons difficult.

If a row or a column of the relationship matrix is empty, a reasoning error might have occurred. If a row is empty, a design requirement addressing a certain customer requirement was omitted. If a column is left empty the corresponding design requirement will be unnecessary and will not contribute to satisfy a customer requirement. The relationship matrix is therefore useful in assisting a design team if it is used as a logical thinking tool to reduce oversights and illogical decisions.

1.1.2.2.6 Importance of DR's

The absolute importance of a design requirement is calculated by adding a column of the relationship matrix after each entry has been weighed by the degree of importance of the customer requirement:

$$AI_j = \sum_{i=1}^{m} W_i R_{ij} , \qquad \text{... (1.1)}$$

where AI_j is the absolute importance rating of DR_j, j = 1,.., n and W_i is the importance rating of CR_i, i = 1,...,n. R_{ij} equals the value that represents the strength of the relationship between CR_i and DR_j.

The relative importance rating is calculated by normalising the absolute importance ratings so that they add up to 1:

$$RI_j = \frac{AI_j}{\sum_{k=1}^{n} AI_k} , \qquad \text{... (1.2)}$$

Once the relative importance of design requirements are determined, trade-off decisions may be made to decide to what extent the design budget should be spent on implementing these parameters.

Measurable targets are set according to the relative importance of the DR's. The more resources are spent on a certain design requirement, the better the target specification would be, and the less risk should result.

This section on the "floor" of the house is also used to do competitive benchmarking with relation to the competition or alternate designs. This is one way of measuring the technological gap between the design team and its competition. Potential innovativeness could also be assessed. If a product is only marginally better than its competition, it may show less of in impact on the market.

1.1.2.2.7 Relationships between Design Requirements

Conflicts and interdependency between DR's are evaluated in the "roof" of the House of Quality. This provides useful information for trade-off studies. If two design requirements are closely related, addressing them collectively might save resources. These relationships are included in mathematical calculations relating the CR's to the DR's.

1.1.2.3 Multi Criteria Decision Making (MCDM) to calculate a HOQ matrix

The 9-3-1 method of rating the performance may be too subjective when deciding relationships between CR's and DR's. Park and Kim [16] suggested that Multiple Criteria Decision Making techniques should be used for this measurement. There is no scientific basis for using for example a 9-3-1 or 9-5-1 technique.

Although better techniques are used, it must be noted that a House Of Quality and other QFD techniques are thinking tools and their results are not cast in stone. Using these better techniques might allow a certain variable to stand out that may not have been noticed if their scores have been closer.

In the case of this study, a decision was made to use MCDM techniques because it would facilitate computer based matrix calculations. Objectivity is increased and difference in importance between the DR's are highlighted more by using these techniques.

1.1.2.3.1 The MCDM method

The method suggested by Park and Kim [16] involve the collection steps to calculate the HOQ. First obtain the following information:

- determine customer requirements;
- perform a pairwise comparison of the CR's using the Analytical Hierarchy Process for weighting;
- determine design requirements to satisfy CR's;
- determine relationship ratings between CR's and DR's by using Multiple Criteria Decision making techniques;
- determine the correlations between DR's;
- gather information about competitors for benchmarking purposes.

After the information has been collected, the calculation is performed by implementing the following steps:

- calculate the normalised degrees of importance of the Customer Requirements using the eigenvector method described by Saaty [20,21];
- normalise the relationship values between CR's and DR's. The correlations between DR's and other DR's are taken into account when this comparison is made;
- calculate the absolute importance ratings of DR's. These values will be normalised because of the calculation in the previous step. Therefore these values will also be the relative importance ratings.

The steps suggested and described above differ from the usual QFD calculation only by suggesting that Analytical Hierarchy Process (AHP) techniques should be employed when calculating the QFD Matrix when using MCDM techniques. (AHP is a widely used MCDM technique developed by Thomas Saaty and described by Winston [21]).

1.1.2.3.2 Determining the relative importance of CR's by using a pairwise comparison matrix

A Pairwise Comparison Matrix (PWC) is an n-by-n matrix, A, so that a_{ij} is the entry in the j the column of row i. The entry a_{ij} indicates how much more important CR_i is compared to CR_j using a scale from 1 to 9, a:

- 1 indicates that the CR's are equally important;
- 3 indicates i is weakly more important;
- 5 indicates i is more important than j based on experience from an expert;
- 7 indicates i is demonstrably more important;
- 9 Cr_i is absolutely more important than CR_j.

A vector, w_{max}, can be calculated that approximates the importance weights of the customer requirements if A is a consistent matrix. The matrix, A, is a consistent pairwise comparison matrix if $a_{ij} = 1/a_{ji}$ decisions are consistent. If CR1 is twice as important as CR2 and CR3 three times as important than CR1 then CR3 should be 6 times more important than CR2.

w_{max} is calculated in two steps:

Step 1. Calculate A_{norm}, where each entry is calculated by

$$a_{ijnorm} = \frac{a_{ij}}{\sum_{k=1}^{n} a_{ik}} \qquad \text{... (1.3)}$$

Step 2. Calculate the weight vector $w = [w_1,..,w_n]$, where the rows of A_{norm} is averaged

$$w_i = \frac{\sum_{k=1}^{n} a_{ki}}{n} \qquad \text{... (1.4)}$$

The consistency of the matrix can be calculated in four steps. These steps are shown in Appendix E. A consistency index, CI, is calculated and divided by the Random Index (RI) that is looked up in a table for a certain value of n. If $CI/RI < 0.10$ then the pairwise comparison matrix is consistent.

The random index, RI, depends on the dimension of the pairwise comparison matrix and is shown in Table 1.2.

Size of matrix	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Table 1.2 Average Random Consistency (RI) as shown in [1]

1.1.2.3.3 Determining relationships between CR's and DR's

Park and Kim [16] suggests that a Simple Multi-Attribute Rating Technique (SMART) procedure, namely the swing method, is applied:

Step 1. Take a CR (A row of the comparison matrix of the HOQ). Rate all DR's that are not related to the CR as 0. View the worst case scenario that would arise if the remaining related DR's are not included (rated as 0) and the best case scenario is all related DR's are included.

Step2. The design team must select the DR that will make the most impact on the CR by its inclusion.

Step3. Assign a rating of 100 to this DR. Rate the other DR's on a scale from 0 to 100 regarding their individual inclusion if the worst case scenario exists.

Step 4. Normalise the ratings so that they add up to 1.

This method is suggested because it would reduce the influence of the subjective 9-3-1 weighting scale. The aim of this study is not to research the best SMART, or any other technique. The method suggested from the research conducted by Park and Kim [16] will also be used in this study.

1.1.2.3.4 Determining the correlations between DR's

Set up a symmetrical n-by-n matrix and use a 9-3-1 rating system to rate the relationship between DR_i and DR_j. 1 indicates a weak relationship, 3 indicates a medium relationship and 9 indicates a strong relationship. Let γ_{kj} indicate the relationship between DR_k and DR_j.

1.1.2.3.5 Normalising relationship ratings between CR's and DR's

Park and Kim [16] suggest that the relationship matrix should be normalised to generate more meaningful representations of DR's and suggest from their own research,

$$R_{ij}^{norm} = \frac{\sum_{k=1}^{n} R_{ik}\gamma_{kj}}{\sum_{j=1}^{n}\sum_{k=1}^{n} R_{ik}\gamma_{kj}} \quad for i = 1,\ldots,m; j = 1,\ldots,n \ , \qquad \ldots (1.5)$$

where the symbols have been defined in previous sections.

1.1.2.3.6 Calculating the importance ratings of DR's

The absolute importance ratings are calculated by using equation 1.1. These ratings are already normalised because all the HOQ information used in the calculation was normalised. The relative importance of the design requirements is now available to use in the design.

1.1.2.4 Using QFD as a measurement of potential innovativeness during design

The QFD process refers to a whole design philosophy. This study is concerned with the early stages of the QFD process, where the HOQ is used to

- prioritise customer requirements;
- establish the relative importance of design requirements at system level;
- establish Technical Performance Measures to quantify these design requirements;
- and to allocate technologies to fulfil these design requirements.

The remote access device is an example of incremental innovativeness. Therefore customer feedback at a redesign stage is very important. If a wholly new device is designed, customer feedback would have less of an impact on the design and a developer would literally have to guess how choosing one technology over another would please the market. Because of the impact of customer requirements on this type of innovation, they may be used to measure potential innovativeness of the product.

The better the extent to which the design requirements and technical performance measures can fulfil requirements of the customer, the more potentially innovative the product will be. It must be remembered that the customer requirements in our case refer to functionality that would not be available in the marketplace. This would satisfy the newness requirement for a product to be innovative, albeit incrementally and not radical.

1.1.2.4.1 Optimisation constraints

The optimization of design requirements is constrained from the perspective of a design firm by

- the cost of components;

- the availability of technology and tools;
- and the skill level of the design team.

The cost of component and materials is a customer requirement in the case of the remote access device. This has come about because of the fact that the market will more than likely not accept a remote access device that is significantly more expensive than the commonly used key ring devices.

1.1.2.4.2 Using design requirements to select optimal technologies to implement in a design

Design requirements should be measurable and are determined with the input from experienced engineers. The DR's represent potential innovativeness measures, because they were determined with the input from the client.

At each level, technologies are selected to address design requirements at a higher level. This may be done using a House of Quality at each level as described in previous sections.

1.1.2.5 Summary of literature review of innovation and QFD

A systematic approach should be taken to design a product so that resources are not wasted on a poor design. The QFD process is used in the preliminary design stage to assist with the construction of a user requirement statement (it is an iterative process). The closer a URS reflects the wishes of the client the more potentially innovative a product may be. By using Multi Criteria Decision Making techniques, and especially the latest methodology in applying Thomas Saaty's Analytical Hierarchy Process, a clearer picture of design requirements may emerge. The design requirements may more closely reflect customer requirements by using techniques that have been proven to work better by other researchers.

In accordance with the system engineering approach, the user requirement statement is an important document. It is written and refined by the design team after a full discussion with the client. Any changes made to this document could potentially have a large impact on the the whole design process. These penalties could be in the form of time delays and design and development cost and would increase the risk of the product being a failure.

1.2 A procedure for innovative design

An important contribution of this study is a procedure for cost-effective innovative design. Information was collected about the benefits of marketing an innovative product and the description of techniques to represent the voice of the customer during the early design stages of a product. From this information, a procedure to design an innovative device was constructed.

1.2.1 A method to design a quality product and to measure its potential innovativeness

When referring to incremental innovativeness of a product, the wishes of the client are taken into account when deciding new functionality that should be included in a new design. The HOQ construct of the QFD process provides a method to translate customer requirements into design requirements. Such a process is described as part of a case study in chapter 2.

The HOQ construct (in essence the link between technical and user requirements) will also be used to verify the design procedure after the device has been prototyped. The assumption is made that the HOQ reflects the customer's requirements. The question that should be answered is: "does the device conform to the technical requirements?" If this is verified, the development procedure will be a success since a close link is made between customer and design requirements.

1.2.2 A quality product: a new universal remote access device

From an end-user's perspective, the initial version of the remote access device is useful. The end user wants to access a remotely activated device by simply activating a switch. The user is not concerned with technical details such as transmitter frequencies, code types or setting codes with selection switches.

There remain logistical problems from a manufacturer supplier and installation company (system installer) point of view. Different types of remotely accessed devices require different types of transmitters for access. This would necessitate the installation of another device and would be expensive for the user and limit market interest regarding the product.

To test the possible techniques of improving the design, the remote access device will be redesigned using the proposed design techniques. Verification of the technical results will be sufficient from a development point of view, with verification from the market considered to be a sufficient condition for acceptance of this quality design process.

To test if the new device is perceived to be better than the previous device, all available system installers will be surveyed. The system installers would be in the best position to assess the wishes of their clients since they have access to the largest number of customers. The new device is aimed to also improve the level of service that they are able to provide their clients, in effect making system-installers part of the user list.

2. CASE STUDY: A NEW UNIVERSAL REMOTE ACCESS DEVICE

To assess whether applying the QFD process to an engineering problem would result in an incrementally more innovative product, a case study is presented. Initially, a vehicle-fitted remote access device was innovated, but was not as successful in the marketplace as was initially hoped. It was decided to attempt another design and use a systematic engineering process that included Quality Function Deployment, as described in Chapter 2. The innovation process of a new remote access device is viewed form the perspective of the design firm. Available resources must be optimally employed to fulfil the wishes of the client as closely as possible but within the resource limitations of a small design firm.

2.1 A description of the device

An entrepreneur patented a remote access device that is fitted to the bright light circuit of a motor vehicle. The intention was to supply a user with a remote access device that was always available for accessing, for example, motorised gates. The batteries on the device need not be replaced regularly.

2.1.1 A description of the initial product

The remote access device is fitted inside a motor vehicle and connected to the normally open bright-light circuit of a motor vehicle. When the bright-light is activated for a second, the remote access device transmits the same code as a key-ring remote access device would when the transmit button is pressed. A remote access device may have up to three buttons, to open for instance multiple garage doors and electric front gates or deactivate alarm systems. More than one button on the device may be simulated through flashing the bright-lights of the motor car twice or three times.

This product and its corresponding patent is already an example of an innovative device. It reduces the reliance on keyring transmitters that could fail due to

- physical loss of, or
- damage to the transmitter, or

- loss of battery power.

These features may be used to market the product as an essential safety device. A remote controlled alarm or gate opener may be accessed from a greater distance due to the higher available transmit power. This is possible due to the fact that a battery of greater capacity is available in a motor vehicle in comparison to the small battery that is used with a keyring transmitter. Due to available technologies it is possible to be even more innovative with respect to this device.

2.1.2 Shortfalls of the existing product

The initial product that was developed in accordance with the patent has the following identified shortcomings:

- a different transmitter model has to be manufactured for each type of code;
- a different model has to be manufactured for each different Radio Frequency including different software for each type of transmitted code;
- the code has to be manually set with switches (Dual In line Package (DIP) switches), and it is not always possible for an installation technician to identify the code that is being transmitted. This is because some transmitter devices do not allow you to set a code using DIP-switches, but a code is electronically programmed onto an IC;
- to change the code would require the device to be removed from the motor vehicle, opened and the physical DIP switches re set to the new code;
- and the cost of manufacturing multiple devices for each of the different codes is limiting the potential profit margin. Different amounts of stock have to be manufactured for the different codes according to the need at different areas. The installation companies also have to monitor their stock carefully to meet the demands of users of the different codes in their respective areas. It is clear that the cost of the logistics involved in monitoring the stock levels impacts negatively on input costs of both the manufacturer and end-user supplier, and therefore profit margins.

2.2 Design history

2.2.1 First design iteration

The patent holder asked a small design team to design a device according to his specifications. It was initially thought that the novelty of having an always available remote access device in your motor vehicle would be innovative enough to satisfy the market.

The device is basically a microprocessor and a RF transmitter. The microprocessor generates the correct code that is set using DIP switches. Initially only a UM3750 code (a basic access protocol that has become a standard) was implemented. To transmit at different frequencies the RF components were changed but the circuit remained the same.

The first device took 6 months to design. Two software engineers used one man month to complete the software code for the project. A hardware engineer took approximately one man month to complete the circuit design. A design for the housing of the device was also done in this period.

After the completion of the first device, a request came from the market that the device must also access devices that utilise other types of popular codes and that the transmitter range should be increased. When the transmitter is placed inside the motor vehicle, the range is decreased because of the metal body of the vehicle that forms an attenuator.

One man month was used to write the software code to add two new codes, namely a "French rolling code" and a "Motorola Trinary" code. A redesign of the RF unit that took three man weeks was also undertaken. The redesign process was completed in six months.

The result was that three devices were manufactured, one for each type of code. An additional device was needed if the code was transmitted at a different frequency, thus resulting in 6 different devices for three codes and two frequencies.

2.2.2 The need for further improvements

The first versions of the vehicle-fitted remote access device were well received by the client and the end-user. The end-user has "always available" remote access at his or her fingertips. The client and manufacturer, however, had a logistical problem that had to do with the manufacturing of different devices for different situations and the training of people to properly install the devices in a motor vehicle.

The client support system was also providing some problems. System installation companies have to train technicians to carry out complicated tasks in addition to just the basic installation of the device into a motor vehicle. The technician also has to recognise what type of code a potential client uses. A client typically only has a handheld remote device and the installation technician needs to open the device and determine the following:

- the type of code, namely UM3750, French Rolling Code, or Motorola Trinary;
- the specific code sequence set by DIP switches;
- the frequency by looking at a value on a resonator or other RF component.

A universal device was required to replace all types of transmitters. This would reduce the hassle for both the manufacturer and the client. The client will also own a multi-functional device that is suited to more applications. Figure 2.1 illustrates this idea. In stead of having to use several different units to accomplish remote access, a single device would provide the same functionality.

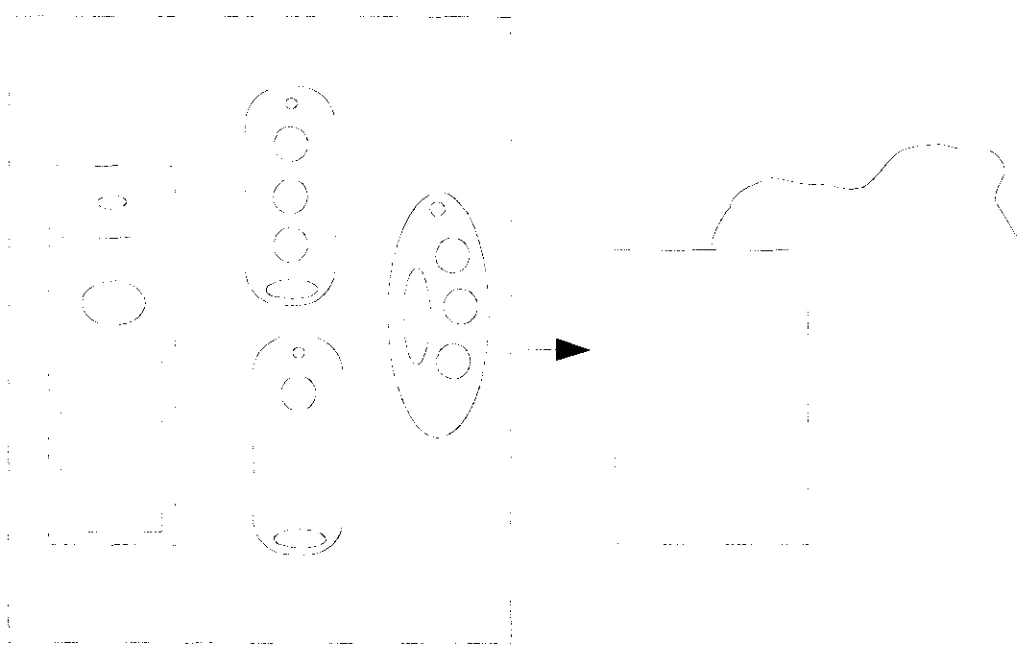

Figure 2.1 A universal device that replaces different types of remote access devices

2.3 Methodology and design

To measure the success of the research conducted into the effective design of an innovative device, the QFD and systems engineering processes were implemented in the design of a new remote access device.

The design process was divided into two phases as illustrated in figure 2.2. A structured system engineering approach was followed to design the device (Process 2). At the initial stages of a system engineering process, decisions were made about which technologies were to be used in the improved design. This decision-making process is described by process 1.

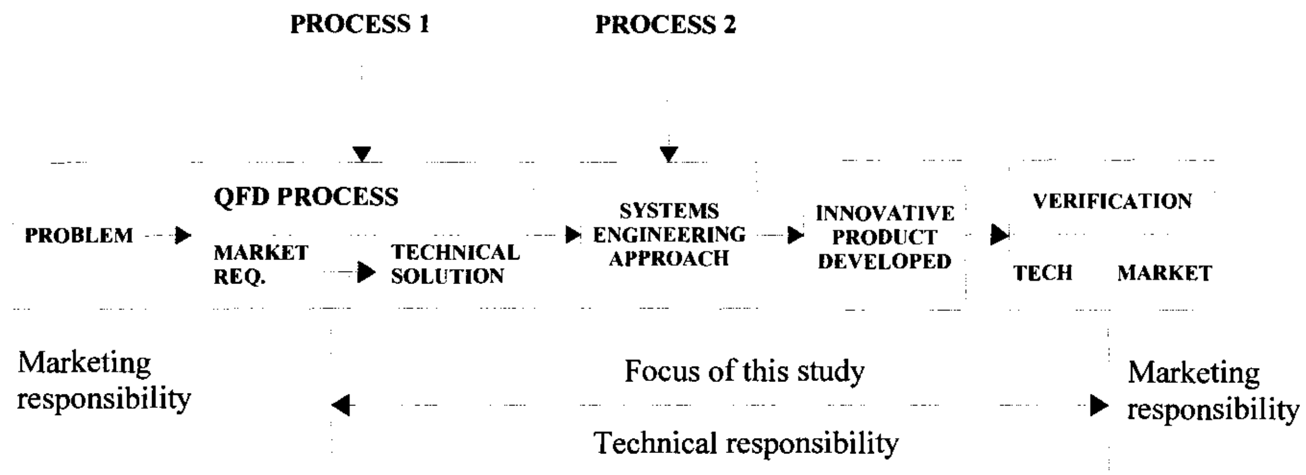

Figure 2.2 Design Process

The design methodology that was followed to design the remote access device is described in chapter 3. This chapter describes how:

- a measurement of degree of potential innovativeness was made using a HOQ structure of the QFD process;
- how the construct was used to transform market (profiled user) requirements into measurable technical solutions;
- how the potential innovativeness of a new device compares to the old device;
- how the system was designed;
- how market success of the new product compares to the market success of the old device.

Finally, verification of the improvement in the development process is given. In the case of the remote access device, evidence must be provided indicating that the improved device was marketed and that the device complied with the wishes of the client as identified by a QFD process.

3. CONCEPTUAL DESIGN PHASE

3.1 Quality Function Deployment employed

In this chapter, it is illustrated how QFD was used to identify user requirements. This process was also used later for identifying design requirements. This information from the QFD process was used to decide what technologies were eventually used in the design.

3.1.1 Use of the QFD process in the design of the device

To optimise the impact of the innovation process, the whole remote access device had to be redesigned from the onset. The idea that a remote access device should be fitted to the bright light circuit of a motor vehicle had to be implemented without falling back to the initial design.

For this design to be potentially innovative, the wishes of the client were taken into account in an effort to be fulfilled closely. The end-user requirements were well understood by the client and did not involve technical specifications.

3.1.2 Identification of customer requirements

The Customer Requirements or CR's that were identified (as obtained in a QFD exercise involving the client) as inputs to the initial House of Quality (HOQ) are:

- CR1: Re use of existing equipment (modularity) – IND
- CR2: Safety (product) - SAF
- CR3: Ease of use (manability) - EOU
- CR4: After sales service and support (maintainability) - SUP
- CR5: Cost (of system) - COS
- CR6: Security (personal) – SEC

Each of the customer requirements is described in the following paragraphs.

3.1.2.1 Independence through the use of existing equipment

The remote access device must be compatible with currently available products in the marketplace as much as possible. It should not be a requirement for a person that want to use this remote access device to change already installed equipment to be compatible with it.

3.1.2.2 Safety

Safety includes safety to the user and safety to the environment. Because the remote access device transmits RF signals and has to be installed in a motor vehicle, certain safety considerations had to be taken into account. The transmitter should not interfere with any of the electronic systems present in a motor vehicle because it will affect the safety of the occupants and other road users. Emissions must be within the limits set by the appropriate regulatory authority.

3.1.2.3 Ease of use

The user should be able to select and transmit a code without effort. The transmitter device should also be easy to program without removing the device from the motor vehicle.

3.1.2.4 After sales service and support

The end user's remote access requirements might change from time to time. In practice this may, for example, be the result of the need for access to a different gate. This creates logistical problems for an installation company.

If the installation company could supply a universal device that would work with all types of code and at all frequencies, the device could be reprogrammed without removing it from the vehicle. This would limit the cost to the client when remote access requirements change and make the product more attractive to potential clients. The client would only need to drive to his service provider and have the device reprogrammed.

3.1.2.5 Cost

Specifying the cost of the system as a customer requirement may lead to misleading results from the QFD calculation. When designing a product, it must work properly in the first place. A client might be willing to pay more for a product that works well rather than a cheaper product that does not really satisfy the user. Cost should rather be used as a constraint when trade off decisions are made. In the case of the new remote access device, cost is important because if the units cost too much to manufacture, supply and install, even given extra functionality, the client will continue to to use the industry standard handheld remote access devices.

The client divided the marketplace into certain sections as illustrated in figure 3.1. The mass market consists of relatively inexpensive keyring remote access devices. This is the competitive section of the market. If cost could be kept in check, this section of the market could be convinced to pay a little extra for a number of useful features.

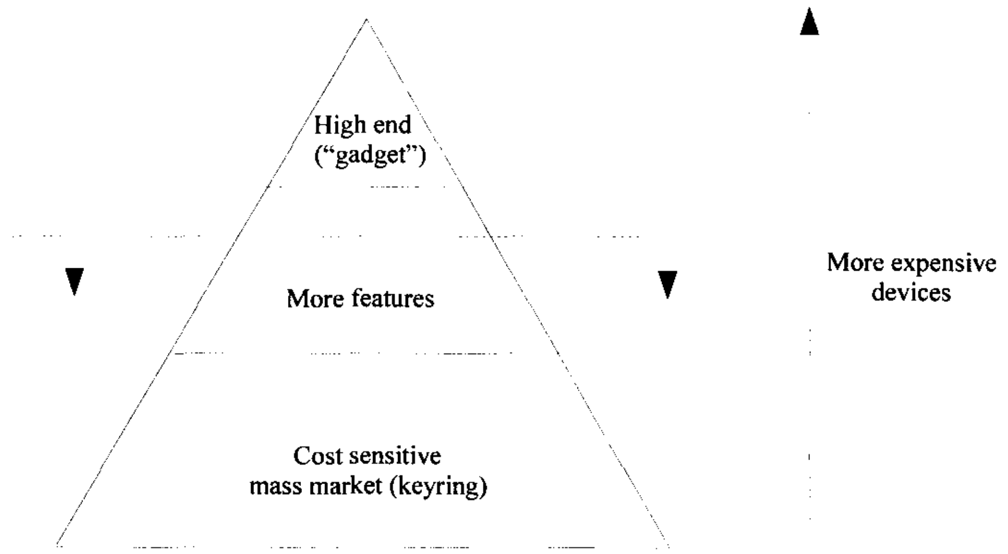

Figure 3.1 The remote access device market

3.1.2.6 Security

The user wants an always-available system in case of an emergency. A person does not want to stop and wait unnecessary for a gate to open and possibly be hijacked. The remote accessed device should be able to be activated fast and from a reasonable distance.

3.1.3 Shortfalls of current product with regard to the customer requirements

The measurement of innovativeness of the device may be viewed from different perspectives. We need to view this measurement from the perspective of a design firm. The goal should be to maximise the customer requirements by employing new design requirements. A new device will be incrementally innovative if it would include all design requirements that are necessitated by the requirements of the customer.

There are numerous installed remote access equipment available in the market. It would be costly to replace all these products. CR1 refers to the fact that a potential client wants to be able to keep the current remote access receivers (installed at access points) if he or she want to use the remote access device that is fitted inside the motor vehicle. The initial product only supported one type of code per device. If a user wants to convert to the motor vehicle fitted device, he or she needs to make sure that all the receiver devices are compatible with this device.

The initial device conformed to CR2. It was fitted inside the engine compartment of a motor vehicle. A hard plastic casing with rubber seals at openings protected the electronic components from corrosive substances that are commonly associated with the engine compartment. The RF power output was at legally allowable levels and at legally allowed frequencies. Any additional enhancements that were made to the remote access device must not compromise this requirement.

Because of the requirement that the improved device must now be able to learn a code, it is necessary to include a user interface. The device must also be easy to operate. CR3 requires that the device must not be difficult to use and if an error occurs, the kind of error must be indicated clearly to the user. Errors would mostly include an unsupported type of code. The type of code that is learned must also be indicated to the user. With the initial device a fixed length code could be changed, by selecting DIP-switches. Another ease of use issue is the activation of the device. The initial device was easily activated by flashing the bright light circuit once, twice or three times to access three different access points.

The initial remote access device did not support all remote access devices because it worked with only one type of code and at a single frequency. Therefore CR4 and CR5 were not satisfied completely. Every time another type of gate or door needed to be accessed, another type of device had to be installed in the motor vehicle. This created problems for service providers and it became difficult to provide support. It would be impractical and costly to install more than one device in the motor vehicle (only one bright light circuit is available in a motor vehicle).

Support rendered to the customer and supplier (CR4) is also important. A single device, which would automatically detect and learn a code and frequency, would decrease the complexities surrounding installation. With the initial device, the installation technician had to figure out what the type and frequency of the customer's remote access transmitter was, select the correct device if it was in stock, and set the correct DIP-switches. The final step was to test the programmed device to see if the remotely accessed device may be operated with the device. A new device that learns the codes and tests the transmission would decrease the effort of training the technicians.

The cost of components (CR5) is important. The remote access device will only be accepted in the marketplace if the cost of the device is comparable to similar devices. The initial device was made more expensive because different models were manufactured for different types of remote access codes and frequencies. A supplier needed to carry stock of all devices even if the occurrence of a certain type of code may be low. A single device that could be used for all remotely accessed devices would reduce the manufacturing costs and the cost of stocking more than one device. More training was also needed to install different devices as opposed to a single device that automatically learns all codes.

The requirement of security (CR6) is reasonably important. The range of keyring remote access devices are short. This has safety implications if, for example, a gate has to be opened and it is unsafe to wait a while for the gate to open. If the gate open switch could be accessed from an increased distance, there would be no need to wait at the gate, increasing personal safety. The existing device was somewhat limited in range due to a transmitter design that resulted in a limited access range.

3.1.4 Design requirements

Determining the design requirements is one of the most important aspects of an innovation process. Engineering experience is invaluable in this activity. The DR's must be measurable. This will improve the choices that will be made with regard to what technologies to use.

Decisions pertaining to DR's are also very important with regard to the systems engineering approach to design. Decisions made at this stage are almost cast in stone at the latest stages of development. If design requirements change, the whole design will change and time and invested capital are wasted or lost. The more thorough the mentioned decisions in the early design stages are made, the less the chance of redesign at later stages of the systems engineering approach.

The customer requirements are used to decide on the importance of the design requirements. The importance of the design requirements will have a direct influence on the technical requirements. If an optimized set of technical requirements could be established, the potential incremental innovativeness based on the user requirements may be obtained.

The design requirements that are needed as inputs to the initial house of quality (HOQ) may be stated as:

- DR1: Operating distance
- DR2: Functional capability
- DR3: Installability
- DR4: Reliability
- DR5: Complexity
- DR6: Flexibility
- DR7: Accessibility
- DR8: Upgradeability / Reconfigurability
- DR9: Producibility

In the first iteration of a HOQ, the design requirements refer to system parameters. These system level design parameters will be used as inputs to the second level HOQ that will determine technical requirements. These are chosen, by utilising the experience of the design team with inputs from the customer. This process should also include discussions with the client

The House of Quality construct of the QFD process will be used to determine the most important design requirements. The project resources should be applied to realise the most important design requirements first. The HOQ will also be used to determine Technical Performance Measures (TPM's) and Design Dependent Parameters (DDP's).

3.1.4.1 Operating Distance

Operating distance refers to the maximum distance from which a remotely accessed device can be accessed by the transmitter device. The operating distance is measured in meters and measures line of sight transmissions. This requirement was identified because previous versions of the device had a limited transmission range.

3.1.4.2 Functional capability

Functional capability refers to the number of different types of devices that can be implemented in the same circuit. This would allow the device to access a number of different remote access receivers with the same device. The functional capability is measured in terms of the number of devices that are emulated by the proposed universal remote access device.

3.1.4.3 Installability

The design requirement of being installable refers to the time it takes to fit the remote access device inside a motor vehicle. This includes the time to identify the correct code of the client and program the device to transmit this code. This requirement is measured in minutes.

3.1.4.4 Reliability

Reliability includes immunity from interference by the vehicle-environment, e.g. vibration, power surges and temperature. Mean Time Between Failure should be high. A non-corrosive housing must be used in order to protect the device. Reliable components should be used. The device should not require any scheduled maintenance. Reliability is a statistical measurement and is expressed as the average time between failures determined over a sufficiently long period of time under given operating conditions.

3.1.4.5 Complexity

Refers to the user interface in general and to the number of buttons or switches that the user has to remember to press. This requirement is measured in number of buttons or switches.

This requirement refers to the *complexity of the user interface* as opposed to the *functional complexity* of the system. A more functionally complex system would have implications with regard to the time it would take to repair the system or to do maintenance on the system.

3.1.4.6 Flexibility

Flexibility refers to the amount of different codes the device is able to learn and transmit. This includes the different frequencies the code is able to transmit at. Flexibility is measured in terms of the number of different codes (at both of the two required frequencies) that can be transmitted.

3.1.4.7 Accessibility

Accessibility is defined as the time it takes for the device to be accessed and the code transmitted. This accessibility is measured in seconds and it includes the time it takes to find the activation switch (bright headlamp switch) and activate the device.

3.1.4.8 Upgradable / Reconfigurability

This design requirement refers to the time it takes to change the code and frequency of the transmitted signal. If a device has to be removed from the motor vehicle before it is reconfigured and reinstalled it would take more time than if the device can accommodate more than one code or frequency, making the support by service provider companies more difficult. This design requirement is measured minutes.

3.1.4.9 Producibility

Producibility refers to the number of devices that can be manufactured in a month. Enough devices must be manufactured in a month to provide for the eventual need of the market.

3.1.5 House of Quality Information

The requirements of the customer are given an importance rating by using a Pairwise Comparison Matrix (PWC). From this PWC a normalised vector is obtained containing the importance of the customer requirements. Table 3.1 shows the pairwise comparisons for the seven CR's. The customer, guided by some input from experienced perspective of the design team indicated if a CR is regarded as more important than another CR and by how much. The weighting system used is described in chapter 1, page 28.

3.1.5.1 Relative Importance of Customer Requirements

The QFD analysis will help with the drawing up of the User Requirement Statement. The Customer Requirements are closely related to the value system of the client. Robustness and cost of the system are the major concerns of the client. The design requirements will represent the system level specifications. A system-level functional analysis is required to determine the operational requirements.

	IND	SAF	EOU	SUP	COS	SEC
IND(CR1)		3.00	5.00	0.33	3.00	5.00
SAF(CR2)			0.20	0.11	0.14	0.33
EOU(CR3)				0.14	0.33	1.00
SUP(CR4)					3.00	7.00
COS(CR5)						5.00
SEC(CR6)						

Table 3.1 Pairwise Comparison of Customer requirements. Refer to page 41 for the definition of the CR's

The QFD analysis will help with the drawing up of the User Requirement Statement. The customer requirements are closely related to the value system of the client. Robustness and cost of the system are the major concerns of the client. The design requirements will represent the system level specifications. A functional analysis is required to determine the operational requirements.

Independence (a more tangible requirement) is more important than things that do not influence the wishes of the client directly like safety standards and security. Ease of use is implicit to the product and is, as such, not more important than the ability to function together with a wide range of devices.

Safety is not rated above any of the other requirements. Product safety is not the concern of the client and it would not be productive to use this as a marketing factor. This is because the levels of RF emissions is government regulated and this device, like all the competitors, are expected to conform to stringent safety regulations.

Ease of use is not more important than support, cost and security. Ease of use is basically implied with these types of devices. It is not too difficult to press a button. It would not be helpful to emphasise a quality in a product that the user expects to be there in the first place.

Support is more important than cost and security. If customer support is neglected, the device will cost more to install and the client might prefer a competitor.

Cost is more important than security. If the device is too expensive the market will remain with handheld devices that are almost as secure.

If the above pairwise comparison is viewed as a symmetrical matrix, A, then according to Saaty's method [21] a two step process may be followed to obtain a normalized vector indicating the importance of the different CR's:

- calculate A_{norm} by dividing each entry in a column of A by the sum of the entries of the column
- calculate w_{max} by averaging the values in each row of A_{norm}. For the values given in Table 3.1 the normalised vector is:

$$\bar{w}_{max} = \begin{bmatrix} 0.2343 \\ 0.0338 \\ 0.0734 \\ 0.4263 \\ 0.1734 \\ 0.0586 \end{bmatrix} \qquad \text{... (3.1)}$$

Using the normalised matrix and the above vector, the consistency of the comparisons is checked. The CI/RI ratio is calculated as 0.098 using the method given in appendix E. This is just below 0.10 which indicates that the comparisons between customer requirements are fairly

As can be seen, independence is a requirement that can be improved on considerably. Universal devices cover more of an installed base than single use units. The universal remote did not get a full mark on its score because there are popular local (South African) fixed length codes that are currently not being supported by these devices.

Safety is not a differentiating consideration, because all the products conform to legal requirements for RF emissions. Design requirements should merely ensure that current standards are maintained. Resources should not be spent to improve safety.

The motor vehicle fitted device is slightly easier to use than the handheld remotes, because

- there is only one switch to activate the device;
- the battery needs not be changed;
- the device is available at ones fingertips (handheld devices are difficult to access).

The universal handheld device is supported the least. Users have to learn how to program the device on their own. The other two products are usually supported by installers. They install the remote access devices and set the correct codes. Support is one area that design requirements must address. In the case of the motor vehicle fitted device, technicians have to be trained to identify the current handheld remote access system and install the correct device in the motor vehicle.

Handheld devices can be manufactured and sold inexpensively. Design requirements must take into account that the designed product must not be too expensive. More features could attract clients even if the cost of the device is not very low. If the device is a universal device, clients may be prepared to pay a premium for extra functional capability.

The vehicle-fitted device ensures more security than the handheld devices by being an always available device. It uses the vehicle battery which is unlikely to run out of power. The transmitting distance of the universal device is shorter than the single code devices because a variable-frequency oscillator is used and maximum output power and antenna efficiency is usually better if it can be optimised for a single frequency.

If the transmission distance can be optimised for a new device, it would improve the security situation for the user. A remote accessed gate may be opened from a greater distance and the user would not need to stop at the gate and wait for it to open. This will, potentially, reduce the risk of hijackings.

3.1.5.3 Relationships between customer requirements and design requirements

The Swing method of the set of SMART procedures is used to obtain the relationship between CR's and DR's. These relationships are summarised in Table 3.2 where the entries are given in %.

	DR1	DR2	DR3	DR4	DR5	DR6	DR7	DR8	DR9
CR1	0	60	0	80	100	0	90	70	0
CR2	50	0	100	0	0	50	0	0	0
CR3	0	0	0	80	100	20	90	30	0
CR4	60	0	0	0	10	100	0	0	0
CR5	10	100	0	0	0	0	0	0	0
CR6	100	50	80	20	20	0	90	80	90

Table 3.2 Relationship matrix showing the comparison of CR's and DR's determined using a SMART

Independence (CR1) is is influenced the most when flexibility (DR6) is added. Independence is affected by the ability of the device to change the type of code it can transmit. To be able to be a three-in-one device awards this CR 80 percent. Being upgradeable is also a factor because if it is impractical to change the code, the flexibility of the device would be neutralised.

Safety is mostly affected by reliability. If unreliable components are used, they might damage important systems of the motor vehicle. Operating distance has to do with transmitter power. The transmitter power should remain under the legal limit to be considered to be safe to fit to a motor vehicle. Where it is mounted in the vehicle may also affect its interference with the electronic subsystems of the vehicle.

Accessibility and complexity have the largest influence on ease of use. The device should have the minimum number of switches within reach. The system should respond quickly and accurately to any input from the user.

Support is very important. The system installer must be able to quickly identify the type of code that is used by the handheld device of a client, program the device with this code and install the transmitter into a motor vehicle in the shortest possible time. A combination of devices must also be handled.

Cost of the final device is important. The ability to handle many types of code could persuade a potential client to pay a little extra, for extra innovative functionality.

Security is affected by accessibility, operating distance and complexity. A client should be able to open a gate from a distance and without having to stop for a long time at the gate. The client does not want to look for a misplaced handheld device or worry about battery power. The client desires accessibility in a number of seconds without significant physical or mental effort.

The matrix in table 3.2 is normalised by dividing each entry in a row by the sum of the entries of that particular row.

3.1.5.4 Correlation between DR's

Table 3.3 indicates how DR's are related to each other (the roof of the HOQ).

	DR1	**DR2**	**DR3**	**DR4**	**DR5**	**DR6**	**DR7**	**DR8**	**DR9**
DR1		0	0	3	0	0	0	0	0
DR2			3	0	0	9	0	1	1
DR3				0	0	5	0	5	0
DR4					0	0	0	0	0
DR5						0	5	0	0
DR6							0	5	0
DR7								0	0
DR8									0
DR9									

Table 3.3 Relationships between DR's. See page 46 for the definition of DR's

There is a correlation between operating distance and reliability. If the transmitter is reliable, the operating distance will not decrease over time and the system, as a whole, will be more reliable.

There are strong relationships between functional capability and flexibility. Only a flexible device that can handle many codes can deliver the multi functional capability required by the user. A product must be easily upgradeable, otherwise a flexible product would be difficult to reconfigure.

Being installable is closely related to flexibility and reconfigurability. Complexity and accessibility are related. Flexibility and reconfigurability are related.

The relationships between the DR's an DR's are normalised as described by Park and Kim [16]. This is shown in table 3.4. The absolute importance of the DR's is calculated the same way as a normal QFD.

Quality Function or Customer Requirement CR	Importance rating.	DR1 Operating distance	DR2 Functional Capability	DR3 Being installable	DR4 Reliability	DR5 Complexity	DR6 Flexibility	DR7 Accessibility	DR8 Being upgradeable/ Reconfigurability	DR9 Being producible
		Design Requirement(DR)								
CR1 (IND)	0.2343	0.0000	0.2711	0.2605	0.0000	0.0000	0.2816	0.0000	0.1658	0.0211
CR2 (SAF)	0.0338	0.5278	0.0000	0.0000	0.4722	0.0000	0.0000	0.0000	0.0000	0.0000
CR3 (EOU)	0.0734	0.0000	0.0462	0.0154	0.0000	0.3461	0.0769	0.4384	0.0769	0.0000
CR4 (SUP)	0.4263	0.0000	0.2397	0.2326	0.0000	0.0000	0.3148	0.0000	0.1932	0.0197
CR5 (COS)	0.1734	0.0665	0.2425	0.2425	0.0451	0.0000	0.2339	0.0000	0.1395	0.0300
CR6 (SEC)	0.0586	0.0571	0.0000	0.0000	0.1714	0.4143	0.0000	0.3571	0.0000	0.0000
Absolute Importance		**0.0327**	**0.2111**	**0.2034**	**0.0338**	**0.0497**	**0.2464**	**0.0531**	**0.1510**	**0.0165**
Target		250m line of sight	3 devices simultaneously	15 minutes	Reliable technology	One switch (for control)	4 different fixed length codes	5 seconds	5 minutes	1000 units/ month

Table 3.4 House of Quality for the universal remote access device

The HOQ structure, like most multi criteria decision making tools, creates a formal environment to analyse facts that are already known. Most of these are intuitive to a reasonably experienced design team. The process ensures that no detail is overlooked and that the customer requirements are represented at later stages of the QFD process in the correct proportion of their importance.

3.1.5.5 Benchmarking competition and previous devices

The importance of the DR's and the comparison with competitors are used to set a design target for each DR. Table 3.5 lists the performance measures of the competition and the previous device as well as a target value that must be complied with.

Device	DR1	DR2	DR3	DR4	DR5	DR6	DR7	DR8	DR9
Handheld	<50m	1 Device	N/a	reliable	3 buttons	1 code	1s	N/a	N/a
Universal handheld	<25m	3Devices	N/a	reliable	> 3 buttons	3 codes	1s	5 min.	N/a
Initial device	<25m	1 Device	15 min.+ 15min.	reliable	1 switch	1 code	5s	15min.	1000 units/ month
Target	250m	3 Devices	15 min.	MTBF = 7 years	1 switch	4 codes + run length	5s	5 min.	1000 units/ month

Table 3.5 Establishing target values for DR's

The transmission range (operating distance requirement (DR1)) of the target design is increased from close to the receiver to 250m line of sight. This is because of the customer requirement for security. A gate, for example, can be opened from a distance to prevent culprits from waiting at the car. This requirement will be much better than the competition and will increase the potential innovativeness of the target device. Because the relative importance of this DR is only 3%, not too much time and resources should be allocated to this DR.

The functional capability (DR2) of the device is extended to be able to access three different types of remotely accessed devices. Developing a multi functional device would increase the potential innovativeness of the device because it represents a significant portion of the customer requirements.

Being installable (DR3) is kept at 15 minutes. The previous device could also be installed in 15 minutes, but an additional 15 minutes are needed by the service provider to establish the specific code that is currently used by the customer's handheld remote access device. The DIP switches must also be set to the correct code. The configuration time on the new device is shorter.

Reliability (DR4) of the device is expected. If the device is not as reliable as devices that are already in the marketplace, potential clients might regret it leading to a situation of negative innovation.

The complexity (DR5) of the target device remains the same. Only the bright light circuit switch is used to activate the device. The switch is activated once to transmit the first code, twice to transmit the second and three times to transmit the third code. The other devices use a button for each code. The universal handheld device has some additional buttons that have to be set to program the device to transmit a specific code.

The device must be able to adapt to all the popular fixed length codes available in the marketplace. The handheld and initial designs are not flexible (DR6) with regards to the range of codes that they are able to transmit. The universal handheld device is not able to transmit some locally designed code types.

Accessibility (DR7) remains the same for the target device. The access time is a bit longer than the handheld devices because only one activation switch is used. The target device and its predecessor is always available at the fingertips and the devices both use the car battery. The handheld devices are often misplaced and the battery may run out of power at an inconvenient time.

The target device should be easy to upgrade (DR8) or reconfigure to use another code in less than 5 minutes without removing the device from the motor vehicle. In the case of the previous device the device would have to be removed from the motor vehicle and another device should be installed. The universal handheld device is also reconfigurable in a few minutes. The handheld device cannot be reconfigured and a new device needs to be purchased.

In terms of quantity, being producible (DR9) is not a problem. Different versions of the previous remote access device had to be manufactured. Supply logistics became a problem because different stock must be kept corresponding to different types of code. It was difficult to determine how much stock of each type of device must be kept. Only one type of device will be installed in the future eliminating the logistical problem mentioned.

3.1.6 House of Quality analysis

The absolute importance ratings produced by the HOQ calculation indicates that the four most important design requirements are:

- Flexibility at almost 25%. The remote access device must be able to transmit all the popular fixed length codes.
- Functionality at 21%. The product must be able to transmit the codes of three different devices with one device.
- Installability at 20%. The product must be easily and quickly installed. It must not damage the motor vehicle.
- Being upgradeable / reconfigurability at 15%. If the code or type of code is changed, it must be easy to change.

Because of the limited scale of the project it might be obvious to any reasonably able design engineer that this should be the case. It must be remembered that on a larger project the relative importance of the design requirements might not be that obvious. It is also easy to see from the HOQ structure why this is so. An all-in-one device would require the remote access device to be fitted to a motor vehicle to include receiver as well as transmitter modules and a user interface. Because the code detection software might require a larger microprocessor, the device would require expensive components that will not be used regularly.

The ability to transmit all fixed length codes (flexibility) is important to the customer. This is because the customer does not want to buy a new remote access device every time a different type of device needs to be remotely accessed.

Other DR's, for example reliability, gets lower scores. This is not because these are not important, but it is because the client expects them to be taken care of. These design requirements are usually implied in the case of a good design.

Reliability is the design requirement that is the most difficult to measure over short term. The design team should take into account that the maintenance requirements of the remote access device are that it shall not require scheduled maintenance. High quality components should be used that are available in the marketplace.

The transmitting range gets a lower score because it is not a huge shortcoming in the previous remote access device. It is reasonably important that some attention is given to the design. This is because the remote access device has to work at multiple frequencies. Either a broadband transmitter module should be used to cover all frequencies or two single frequency transmitters should be used and switched between as needed.

Complexity and accessibility get low scores because ease of use and security are not rated high as customer requirements and these have the most influence. Most of these issues were resolved with the previous remote access device.

Being producible gets the lowest score because the client is not concerned with how many devices are manufactured per month. It is also difficult to assess the influence that the other DR's have on being producible. It might have a bigger influence when technological choices are made.

3.2 Technical Performance Measures (TPM)

From a systems engineering point of view, the technical performance measures are represented by the design requirements from the quality function deployment. The import parameters that was established include:

- the relative importance of the TPM's calculated with input from the customer;
- the current benchmark of the TPM's (previous device);
- the target benchmark that the design must fulfil.

3.3 Initial system level functional analysis

The functions that any system must perform should be established before technologies are allocated to perform the functions. A design should only be limited by certain technologies when trade-off's are performed and not during an abstract functional analysis. Engineering teams may make some technology choices from experience.

Figure 3.3 and figure 3.4 summarises the system level functions of the device. Note that no choice of technology has been made with regard to the system – this will be done during a resource allocation.

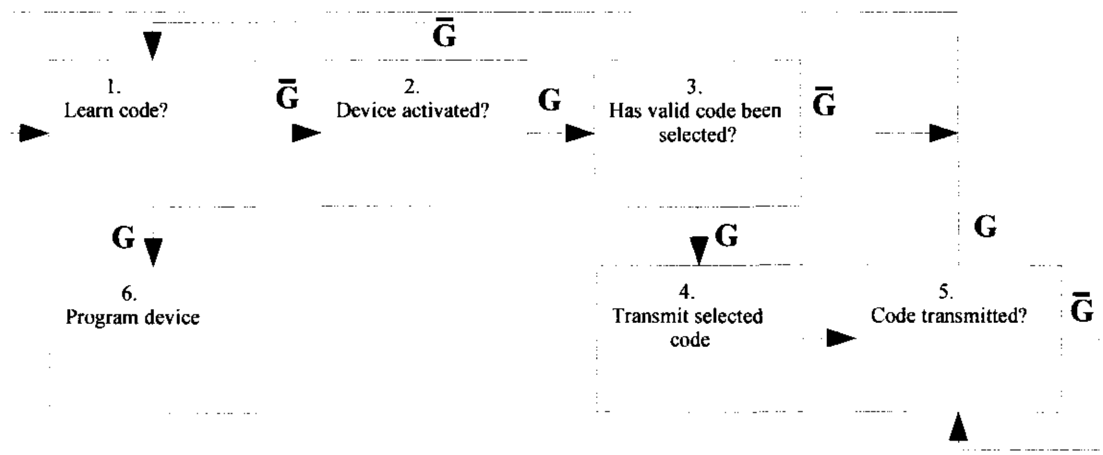

Figure 3.3 System level functional analysis

At system level the device is not complex. It is attached to the bright light circuit of a motor vehicle and is activated by one normally open switch. Flick the bright-light switch once, twice or three times to send a code.

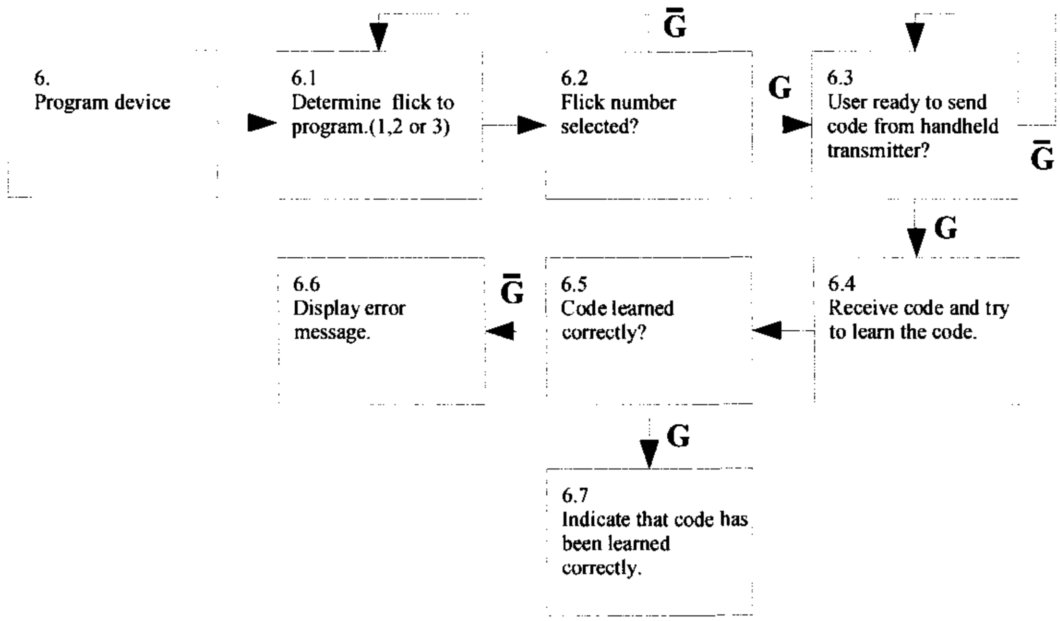

Figure 3.4 System level functional analysis (continued)

For the device to be programmed a user interface is necessary. The device needs to be placed in a programming mode. At least some sort of indicator light is needed to indicate success and an error condition.

3.4 Functional allocation

Related functions are grouped together into subsystem blocks that will perform these functions. High level trade-off's should be carried out and the best alternative should be selected.

3.4.1 Functional packaging

The basic system includes an RF transmitter to physically modulate the digital code onto a transmitted RF signal. A software module is needed to generate the digital signals of the code. Every different code involves different timing variables. An RF receiver is needed to demodulate the received signals into a digital signal. A power supply is needed to power the device. A display is needed to communicate system states and messages to a human operator. A number of button switches are needed for user input to communicate instructions to the device. The receivers and transmitter operate at multiple frequencies. A non-volatile storage device is needed to permanently store a detected code for later transmission. A human operator is also part of the system.

Software modules are needed to:

- detect a type of code;
- decode the digital signals;
- communicate with an operator;
- store and load a code.

Figure 3.5 gives an overview of the functional allocation. The hardware of the device is not overly complex. The RF modules are primarily concerned with translating the codes generated by the microprocessor into a RF signal format that must be received over a distance. The power supply is needed by all the subsystems to function. The main design involves software modules.

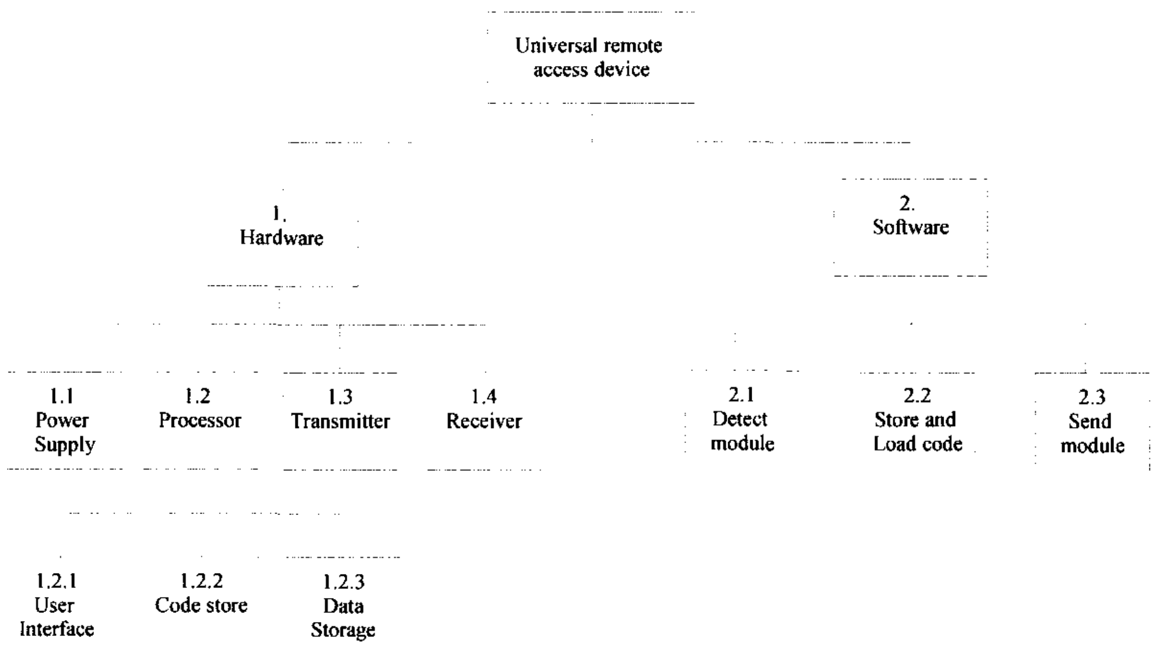

Figure 3.5 Functional allocation

3.4.2 Fixed technologies implemented

Although it is important when any system is designed to conduct a functional analysis of the system before any technologies are decided upon, some of the technologies that will be implemented are known beforehand. In the case of the universal remote access device it is known beforehand that a microprocessor will be used to generate the signals to be transmitted. A microprocessor is also needed to decode the signals that are received.

What is important to the design is the type of microprocessor to use and what the minimum specification of the processor should be.

3.5 Design alternatives and trade-off's

The design team identified 2 possible design alternatives. The first alternative is to design an all in one device that contains the user interface, transmitter and receiver.

Because the customer requires that the cost of components should be kept to a minimum, a wise choice as second alternative may be to split the remote access device into two different devices. A receiver device, called a Grabber, would learn the code from a handheld remote access transmitter. A transmitter device, that would be fitted to a motor vehicle, will then be programmed by the Grabber with the code it learned from the handheld remote. The service provider company would require only a limited amount of receiver modules. The transmitter modules could be reprogrammed without removing it from the engine compartment of the motor vehicle. The results obtained from the HOQ analysis support this choice.

3.5.1 Using the HOQ in a trade-off study

Trade-off studies are necessary to determine the best-case design. If a certain technology is used, certain design parameters will be fixed. If for example a 4 MHz microprocessor is used, it would be impossible to operate a 100 kHz I^2C communications bus at 100% efficiency. External non-volatile memory is attached to this bus. A 20 MHz microprocessor might be able to use this bus at 100% efficiency, but is more expensive. Money would be wasted if the bus is not needed to operate at full speed to satisfy customer requirements.

The following design requirements will not be influenced by either the single unit or the two module design:

- operating distance
- functional capability
- complexity
- flexibility
- accessibility
- producibility.

3.5.1.1 A single unit as solution

If a single module solution is considered, the following considerations need to be taken into account:

- the microprocessor that is used would need more program memory and additional memory to store a received code;
- both a receiver and transmitter module need to be included and therefore the cost of the device would be higher and the device would be bigger;
- external buttons and LED's need to be fitted for the user to operate the learning mode;
- the current housing of the transmitter that is fitted to a motor vehicle would be unsuitable and a new housing must be designed, adding to the cost of components.

3.5.1.2 Separate receiver and transmitter

If separate transmitter and receiver modules are employed, a method of communication is needed between the modules. This communicating method should be 100% robust, reliable, and error free and should be inexpensive in terms of technical solution employed and software written. The separate grabber module does not have such a strict cost barrier. This device may be more expensive since installation firms need only one or two. If separate units are designed, the same housing may be used as the previous device, saving on cost of components.

3.5.1.3 Comparing a single unit and separate receive and transmit units

The three design requirements that are affected by this choice is installability, reliability and upgradeability. Being installable and upgradeable is very important. A design that influences these requirements negatively should not be considered. Table 3.6 shows a comparison between the design alternatives given the influence on the design requirements.

	Influence on design requirement		
Design	**Being installable**	**Reliability**	**Being upgradable**
Single	-	0	-
Grabber device	+	0	+

Table 3.6 Design trade-off (+ = Good choice, - = Poorer choice, 0 = Difficult to determine)

An all-in-one device would be larger than the transmitter only when using separate devices. It would be more difficult to find space to install the device and might influence safety. The transmitter-only device would use up exactly the same space as the initial device and could potentially use the same housing.

The reliability of separate devices might be affected negatively because of the need for a user interface. A reliable device would require a robust user interface that would survive the stresses imposed on it by the harsh environment of a motor vehicle engine compartment. From an operational point of view, both devices will have similar reliability.

The single device would be more difficult to upgrade. It will have to be removed from the motor vehicle, opened and re-programmed. In the case of the split device, the grabber is connected to the transmitter and the battery of the motor vehicle. A new code is learned and the transmitter is reprogrammed. The grabber is then removed.

The most important factor that influences the choice of design is the customer requirement of cost. Much of the development budget is spent on the design requirements of functional capability and flexibility. The processing power required to learn and store many different types of code would require a single device to include an expensive processor with a lot of random access memory. This could potentially double the cost of the final product. To limit the cost of the device would require a cheaper processor with less features. Using a more limited processor would be detrimental to the most important design requirements, limiting the ability to learn all four types of code.

The all-in-one device would include a number of normally redundant components. A client might possibly only change or add a code once in six months and the receiver is used only for the learning process. The receiver and processing power to learn codes are otherwise not used.

The design employing the separate grabber and transmitter devices should be the design to implement. The system installer programs the client system. If the client wants to change the code, he or she will go to the system installer and the code is changed in 5 minutes, complying with the design requirement of reconfigurability.

3.6 Design concept

Figure 3.6 shows a simple block diagram of the envisaged system. The transmitter section consists of a power supply, microprocessor and RF transmitter modules. The grabber section consists of a RF receiver module, a microprocessor, push-button switches for user control and a display to inform and communicate with the user. The transmitter and grabber are connected with a simple, low cost communication system. This system is used to program and test the transmitter system.

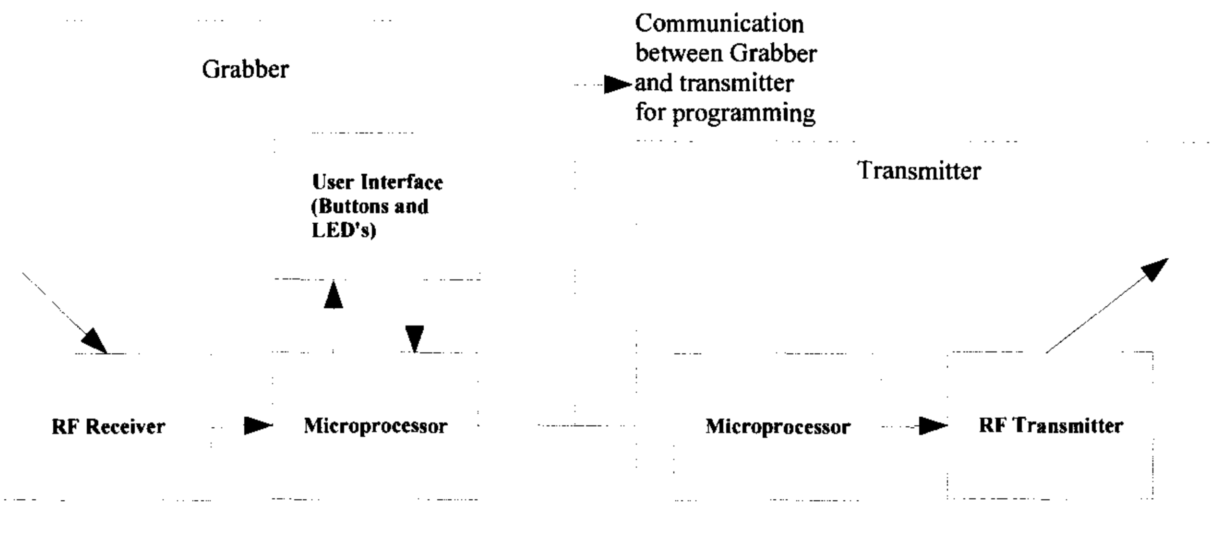

Figure 3.6 Block diagram of envisaged system

3.6.1 The transmitter and receiver

Due to the cost constraint and the design requirement of operating distance, it was decided against the use of a wideband transmitter and receiver. The design requirements of flexibility and functional capability weigh heavily and the device must be able to handle all allowed frequencies in South Africa.

A compromise was found by using two receivers that operate on the two allowed frequencies in the remote access device industry. A dual transmitter device was also used and the microprocessor is able to switch between the two frequencies. In areas where another frequency is used, one or both of the popular frequencies may be discarded in favour of the popular local frequency.

The limitations of wideband devices were sidestepped while the customer is still able to access all the different fixed codes at the different frequencies in his area. The use of the QFD highlighted this problem and also made the solution easier to find.

3.6.2 Design issues that remain and are left to the preliminary design stage

Two issues of the technological design remain, namely the specification of the microprocessors to be used for each system as well as what communication system will be used between the two devices. These decisions are left to the preliminary design stage where Engineering Development Models or Test beds might be built to assess viability.

The make of microprocessor was also fixed at the conceptual design stage. It was decided that PIC microprocessors should be used. The reasons for using PIC microprocessors include:

- favourable component prices in comparison with competitors;
- availability of engineers that are experienced in designs incorporating these devices;
- a low cost in-circuit debugger is available for rapid prototyping;
- and a free Integrated Design Environment (IDE) is available from the manufacturer, along with software support and free software upgrades.

3.7 Summary

With the assistance of QFD procedures, the design requirements were established and a conceptual design was carried out reflecting the wishes of the client. A detailed description can be found in the appendices.

4. PRELIMINARY AND DETAIL DESIGN PHASES

In the preliminary design phase, the same process that was followed in the conceptual design phase is carried out at a sub-system level. If a House of Quality analysis should be implemented at sub-system level, the left-hand side inputs are the prioritised design requirements that were determined in the previous section.

In the case of the universal remote access device, a QFD HOQ analysis at the preliminary and detail design stages was not carried out explicitly as in the case of the conceptual design. Since the technical risk was low, and the cost associated with following a detailed HOQ analysis at lower levels was high, a straightforward systematic design approach was followed.

The detail design of the device is described briefly. Both hardware and software designs were carried out. The design of the enclosure and layout of a user interface were also part of this process.

4.1 Systems engineering techniques used in preliminary design

During the preliminary design phase of a system, a subsystem functional analysis is undertaken to establish the functions that should be carried out in more detail. Resources are allocated to functions and decisions on technologies are made.

4.1.1 Sub-system level functional analysis

Appendix A provides a detailed functional analysis of the system. Functions are expanded so that subsystems may be identified. The grabber and transmitter are connected as required for the mutual communication system to operate and power is supplied to both the transmitter and grabber modules. The grabber is set to learn mode and the number of the code that must be learned is selected. An external handheld remote access device is enabled. The grabber learns the code and indicates to the user that the code has been learned. The user confirms that the transmitter may be programmed. The grabber sends the code that was just learned to the the transmitter device and asks the device to transmit the code. The grabber verifies the code that is transmitted. The transmitter device is asked to stop transmitting. The grabber informs the user and the transmitter device if the code was captured correctly.

The important functions will be performed with microcontroller software. Once it has been decided which microcontroller to use based on the software requirements, the hardware and software detail design is carried out.

4.1.2 Functional allocation

The functional analysis shown in Appendix A also includes, to a large extent, the grouping of the functions into logical software components that will perform these functions. The user interface was implemented with push-button switches and LED's.

The user's manual of the system is included in Appendix D. The functional operation of the system will be insightful when the sub-system level functional allocation is studied.

4.1.3 Synthesis

A number of variants of the PIC microcontroller family are available. A decision must be taken about which microcontroller model to use in the code grabber (receiver and programmer) module and which one for the transmitter module. The second stage of the QFD process, where TPM's are established, will guide the design team to which technologies must be employed.

It was decided that for the sake of software modularity that the microprocessors on both the devices will share the same register memory space. Therefore a transmit software module that is used in the transmitter device, can also be used in the grabber device to transmit commands to the transmitter device using a single short wire.

4.1.3.1 Experimental design

An initial unit was built on a breadboard using a PIC16F877, two receiver modules and a transmitter module. Initial concept testing code was written to detect which receiver was currently receiving (frequency detection) and to generally decode an arbitrary signal and store the result in memory.

Routines were added to identify the different types of code and other modules were added to retransmit these codes. During this phase all the major fixed length code types were characterised so that timing routines and limitations could be established. It was determined that if the incoming signal could be sampled every 50 microseconds, the original signal could be accurately timed and decoded. The software modules were used in the detail design.

It was established that a 4 MHz PIC processor was adequate for these purposes and that the PIC 16F877 had enough RAM registers available to store all types of codes (+-350 bytes) [12].

4.1.3.2 Communication between the devices

Possible technologies to use could include serial communications using one of the communications standards that is supported by the PIC chip, for example EIA-232. The service provider companies required a robust communications technique that would include no physical interfaces that could break off easily.

It was decided that a short wire should be used to transmit bytes directly from one microprocessor to another. Because of the distance of about 20 cm, the communication will be slow. The use of low speed communication is not a problem in this design because even the slow communication would still ensure that the transmitter device is programmed in less than a second. This would still be acceptable to service provider companies.

4.1.3.3 Final design

A second unit was constructed to test the transmitter concept and the communications between the Grabber and the transmitter. The same transmission module was used in the transmitter as with the Grabber module. The Grabber sends commands through the short wire and the transmitter sends its responses via one of the fitted transmitters. The Grabber module receives its replies from the transmitter via one of its receivers. A simplified Stop-and-Wait protocol was implemented. The total Grabber / Transceiver concept was tested with this final design and it was used to develop all the software.

4.1.4 Choice of microprocessor on the transmitter side

It was decided to keep the housing of the original transmitter device. There is not enough space on the transmitter circuit board for the PIC16F877. The surface mount version of the PIC16F628 [11] is smaller and will fit easily into the housing. It is only a fifth of the price of the 16F877 and has a similarly organised register space. It has about half the registers of the 16F877, but it is not required to do processing and comparison of received signals. The only hardware that lacked was enough non-volatile memory to store 3 different codes. A code could occupy 350 bytes so a 1 kB serial Flash RAM device had to be accommodated on the transmitter device.

The external non-volatile memory device added approximately 10% to the unit cost of production of the grabber device. This is justified because it provides for the design requirements of flexibility and functional capability. Additional software modules had to be written for storing and reading from this external memory. The smaller microcontroller does not have built in capability to read from and write to serial memory.

4.1.5 Software design

The allocation of functions to software modules is shown in the functional analysis diagrams in Appendix A. The description of the high-level software design is summarised in Appendix C. The function of each software module is described. Where appropriate, the inputs and outputs of a software module are described and the affected registers are mentioned.

The software design was aided by the use of rapid software development tools. An in circuit debugger was used with a development model of the system. The use of an in-circuit debugger allows a programmer to halt the execution of the program whilst the system is being tested to examine the registers of the microcontroller. This speeds up the debugging of the source code and resulted in a significant reduction of software design time. This reduced the professional fees paid to the software design engineer and reduced the development cost.

The number of assembly language source code that was produced includes:

- +/- 2500 lines of code for the grabber module and
- +/- 1500 lines of code for the transmitter device.

4.2 Detail design

The detail design took only 6 man weeks to complete. The hardware design was completed before the software design was finalised. Because the software was written on a development board using an in-circuit debugger and the design's final hardware devices was based on this board, the software worked the first time on the initial device.

The design of the housing of the grabber device and its user interface was also concluded. The circuit board of the transmitter device was designed so that it would fit into the housing of the previous device.

4.3 Summary

Following proven system engineering techniques, the design was completed on schedule resulting in a functional device that was marketed. The voice of the client was echoed in the preliminary sub-system level design through Technical Performance Measures that were established in the HOQ from the concept design. The importance of these TPM's influenced design choices that were made.

5. RESULTS

5.1 Technical results

A QFD technique was used in the design of the universal remote access device. The device performance with regard to the identified customer requirements is summarised in table 5.1.

Customer requirement	Performance
Modularity (Independence)	Works with all the available fixed length code systems and they will not have to be replaced to be used together with the transmitter device.
Safety	Transmit power is within legal limits. Will not interfere with safety systems of the motor vehicle.
Ease of Use	Just flick the "brights" once, twice or three times.
Support	The code on the device can easily be changed by just connecting the grabber device and learning the new code. The transmitter will automatically be programmed and the code tested.
Cost	Production cost R120. Selling price: R350. This is a very competitive price for the features for a 3-in-1 device with the flexibility of all the most popular codes.
Security	Operating distance increased over previous models. At least 250m line of sight was measured.

Table 5.1 Compliance with customer requirements

A working commercially available device that addresses the requirements of the customer was developed and represents an innovative device. Figure 5.1 gives an overview of the housing and user interface. Note that the communication between the devices is carried out through using a single (the yellow) wire. All that is needed to program the transmitter is to connect the yellow wire and to power the two devices from the same power source so that they have the same followed by modularity and cost. The TPM's (Target values) were also established for the DR's that represent the benchmark for the system's technical design to be evaluated against.

It was shown that, in only six weeks, an improved device was developed as opposed to the previous development that took over six months to complete. This result is crucial to the economics of development and shows that (i) good initial thinking and (ii) a structured design approach (specifically including functional analyses and requirements allocation) are critical elements to a small design firm's success.

5.2 Marketing results

Although conducting a market survey regarding the success of the remote access device was not the main aim of this study, four system installers were asked to answer a number of questions about the perceived improvement of the new vehicle-fitted remote access device in comparison with its predecessor. The response to all the questions were overwhelmingly positive with regards to the new device. Because the system installers are in daily contact with the end users of the product, they are in a good position to give feedback about the perceptions that exist in the marketplace. The questionnaire is given in Appendix F. A summary of the questions and the spread of the answers is given in table 5.2.

Question	***Responses***									
1			***Yes***					***No***		
			4					0		
2			***Yes***					***No***		
			4					0		
3	***-5***	***-4***	***-3***	***-2***	***-1***	***1***	***2***	***3***	***4***	***5***
	0	0	0	0	0	0	0	0	1	3
4			***Yes***					***No***		
			4					0		
5			***Yes***					***No***		
			4					0		
6			***Yes***					***No***		
			4					0		
7	***-5***	***-4***	***-3***	***-2***	***-1***	***1***	***2***	***3***	***4***	***5***
	0	0	0	0	0	0	0	0	2	2
8		***NO RESPONSE***			***LESS AFFLUENT***				***MORE AFFLUENT***	
		1			1				2	
9	***1***		***2***		***3***		***4***		***5***	
	0		0		1		2		1	

Table 5.2 A summary of the responses obtained from 4 service providers of the remote access device

The questions were formulated around the identified customer requirements of range, flexibility, safety, support to the client and cost. The system installers indicated a positive response from their clients with regards to these functions.

The reason why only four service providers were surveyed is that only these system installers were involved with both the new device and the initial device. In addition, the remote access device is still in its infant shoes, and therefore has not been marketed widely and in large volumes. The gradual approach to product deployment is due to the current marketing strategies of the patent holder (a distribution channel has to be systematically created first). However, over 200 units have been installed by these installers and the averaged values of their responses are most definitely significant from a marketing test point of view.

Given these limitations, the response from the market is very positive with regard to the functional improvements made with regard to the identified customer requirements. This is regarded as sufficient evidence to show that the QFD process yielded very positive results as opposed to a less structured development approach that excludes the user.

6. CONCLUSION

By employing a QFD technique at the requirements analysis stage of a conceptual design, the wishes of the customer, client or user are kept in mind through the whole of the design. Choices made in line with these requirements will lead to a product featuring new and improved functionality that is directly aimed at fulfilling the wishes of the client.

If this technique is used, the potential incremental innovativeness of a product may be predicted to a higher degree of certainty, reducing risk. True innovativeness is only accurately measured by market studies after the product has been marketed for a significant time. By using client orientated design techniques, at least incremental potential innovativeness may be predicted. For more radical innovations, the input of the user can be less successfully used because the client does not always know the potential uses of a brand new technology.

APPENDIX A FUNCTIONAL FLOW DIAGRAMS

Figure A.1 Operational functional flow

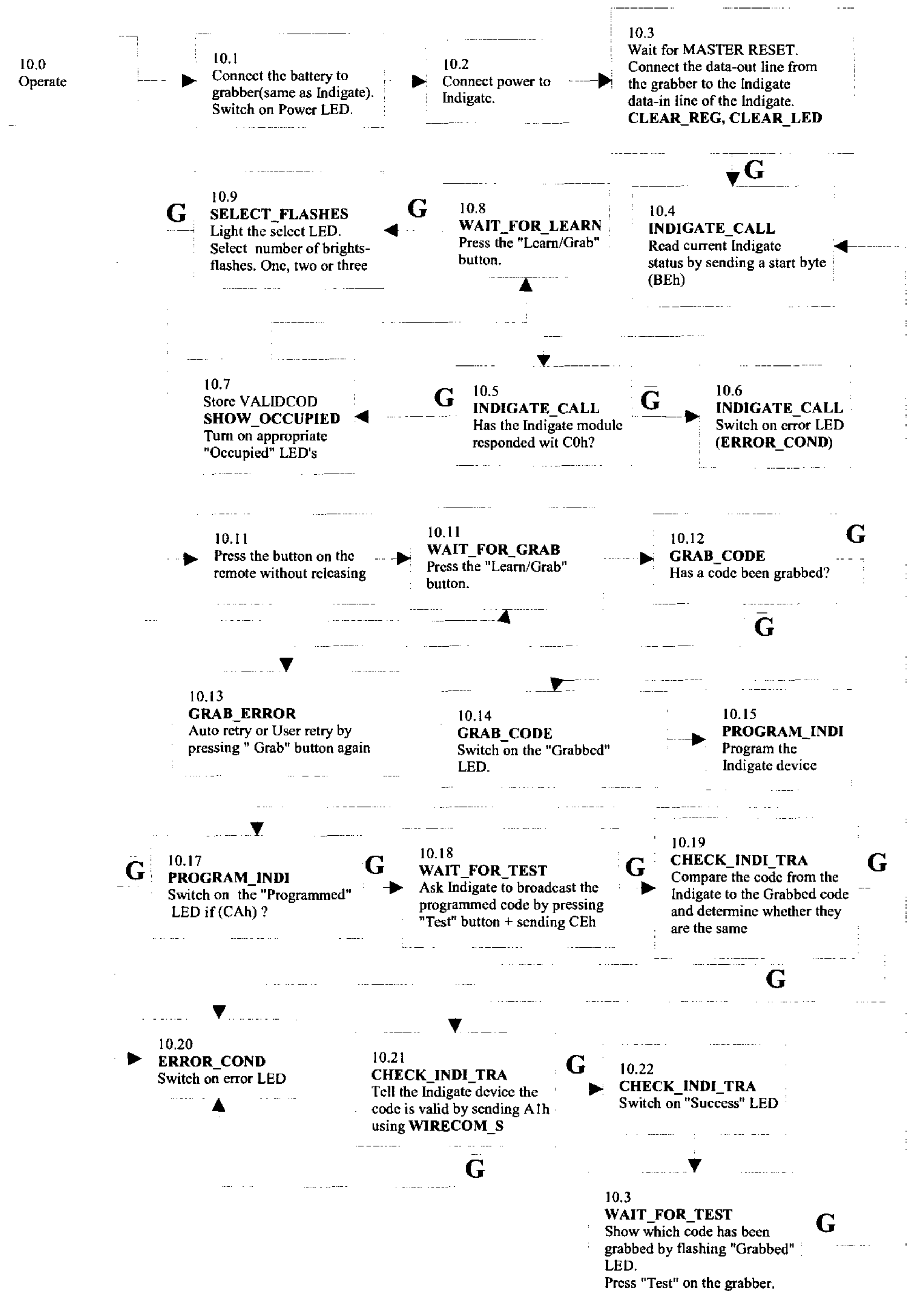

Figure A.2 Functional flow (continued)

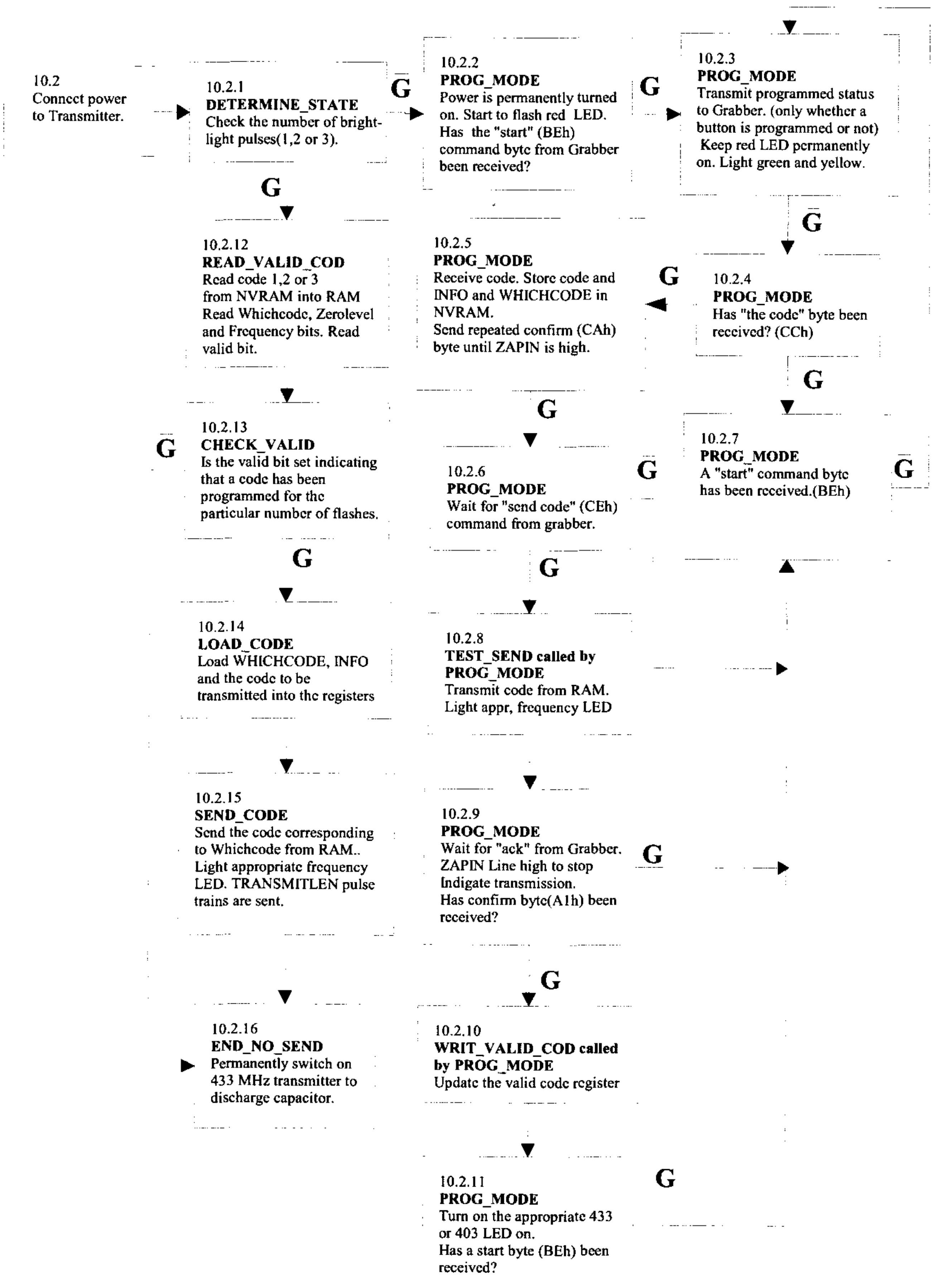

Figure A.3 Functional flow diagram (continued)

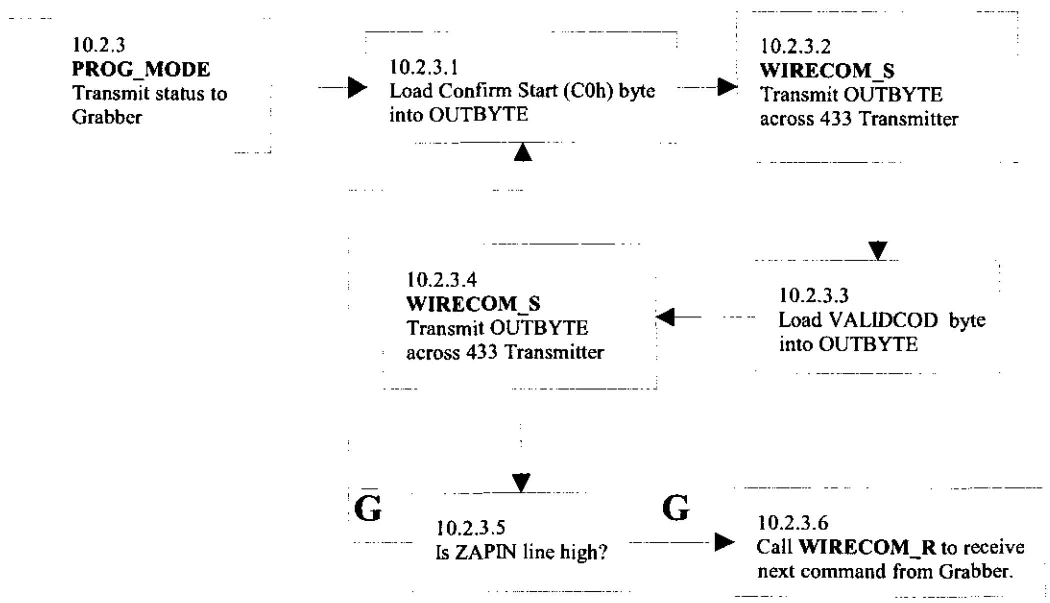

Figure A.4 Functional flow diagram (continued)

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