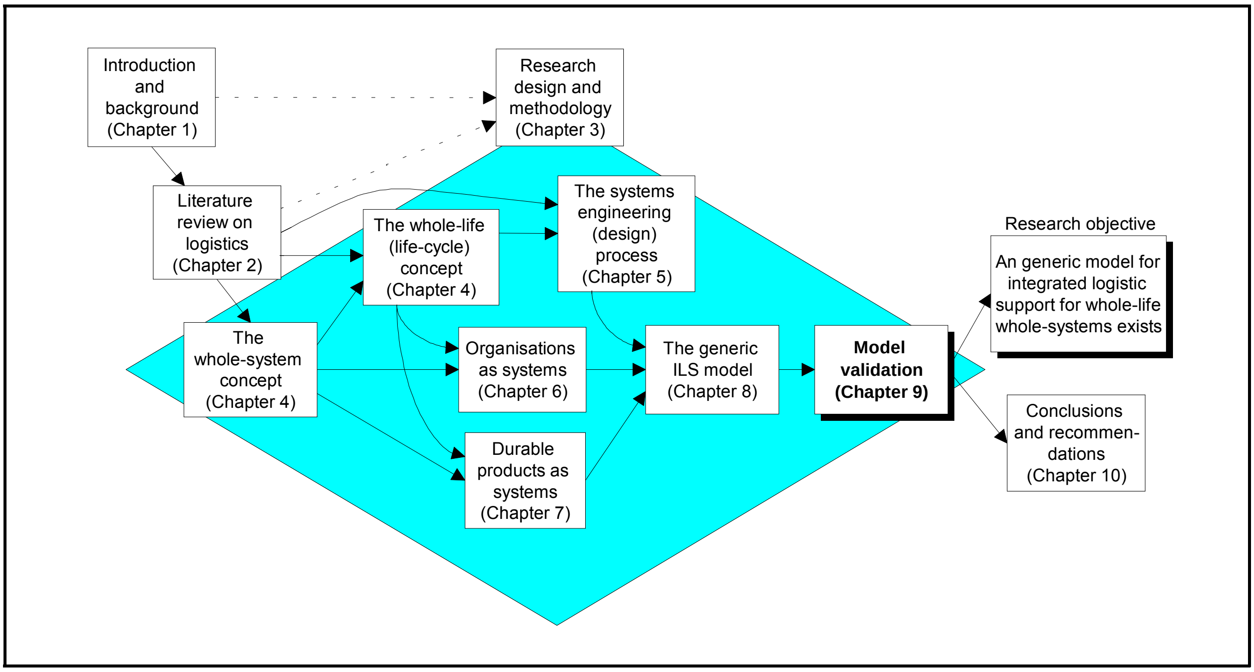
# Chapter 9

# Validating the integrated logistic support model for whole-life whole-systems

*"We can consider models for creation of the solar system without waiting for another creation in order to have observations that will cause a validation or modification of the model."*

Rubenstein and Firstenberg [1995:162]



## 9.1 Purpose and outline of the chapter

The purpose of this chapter is to provide a more formal validation of the model describing the generic approach to integrated logistic support, to the extent that it is possible to provide such a formal validation. As this thesis is concerned with the construction of a model, it is necessary to provide some background to the approach how a model should be validated. The concept of a thought experiment is introduced as an approach to validating the model. A basic thought experiment that has been applied to an organisation as a system, is introduced to show the validity of using thought experiments. The structure of the thought experiment to be conducted for validating the model is then introduced.

The thought experiment is conducted comparing the effects of an approach that does not consider an integrated approach to logistic support, with the effects of using the approach proposed in this thesis, by investigating the impact of the two approaches on overall system measurements. The comparison is done for both the operational support and the maintenance support perspectives of integrated logistic support, while considering both the technical and managerial activities.

## 9.2 Model validation and thought experiments

A models never reflects reality in its totality. If a model is to fully reflect reality, it is not a model anymore, but reality itself. Models are normally homomorphic, which means that a number of real world components are represented in the model by only one modelling component. At best a model comes close to reality and the 'truth'. Models normally have much less content than the real world problem (or solution). Due to aggregation some elements of the real world are ignored causing the model to be homomorphic.

Ignoring some components from the real world may cause the model to be oversimplified or even invalid for understanding and prediction. Whether an element is ignored willfully or by mistake, this inadequacy of models is called error of omission. Sometimes elements are ignored wilfully to simplify the model or to eradicate something from the model that does not fit a preconceived idea. Whitehead in Rubenstein and Firstenberg [1995:161] notes: "*If you only ignored everything which refuses to come in line, your powers of explanation were unlimited*." The second error that is associated with modelling is when more content is included in the model than what exists in the real world. This type of error is call an error of commission.

The process of model validation is shown in Figure 9.1. According to Rubenstein and Firstenberg [1995:161], it is in a sense true that the validation process is never ending, as the figure suggests. They conclude that a model that is supported continuously by evidence and requires no modifications, become valid theory, and the postulates of the model that represents an observed regularity become laws. Not all models can be validated by measurements and observations. For example the models for the creation of the universe or the solar system depict elements and their relationships that will cause creation. Such models are considered without having to wait for another creation in order to have validations or modifications to the models [Rubenstein and Firstenberg,1995:162].

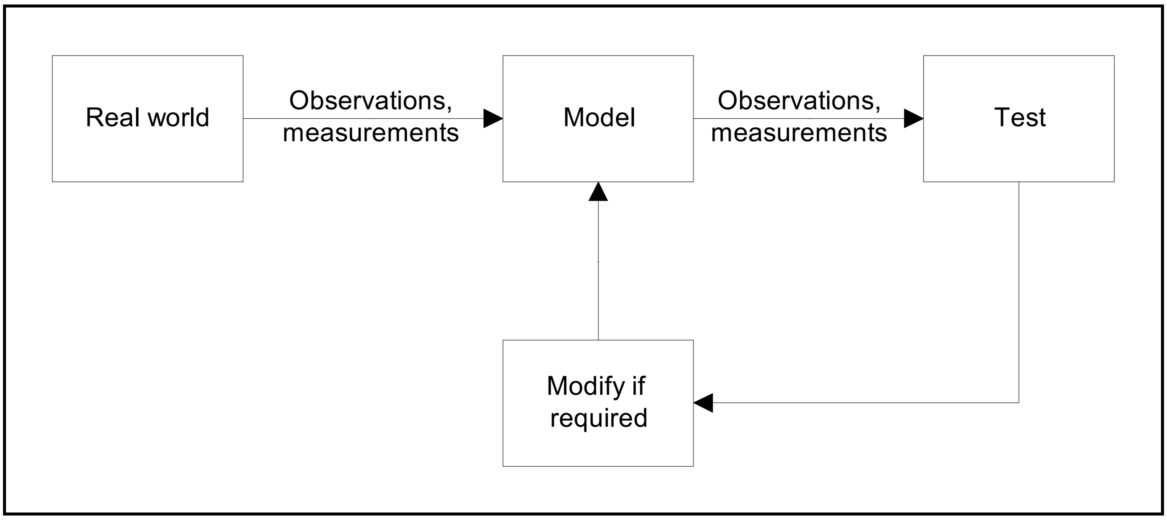


**Figure 9.1: The model validation process**
Rubenstein and Firstenberg [1995:161]

The question that arises is how the model presented in this thesis can be validated. It definitely is not a model in the same category as a model of creation, nor is it a mathematical model which can be validated using primary numerical data. Conceptually the best way to validate the model is to get real world data of systems over their entire life-cycles comparing those systems which follow the approach proposed by the model and those systems which do not follow the proposed model, measuring and observing the effect of management and technical activities performed or not performed on the ability, availability and affordability of the system in question. In order for the comparison to be valid, a comparison has to be made between the life-cycles of organisations of similar size, industry and product/service range within similar economic conditions, such as labour supply and level of training, accessibility to other resources and economic climate. This is to ensure that the measurements are not skewed by external factors. The same has to be done for product systems. The above requirements set for validation of the model seems to be an impossible task. The first reason for the impossibility of such a validation is that the life-cycle durations may be of such a substantial length, that the validation will take many decades to complete, as the life-cycle duration of the average organisation is in the order of 40-50 years [De Geus, 1997:7]. The second reason for the impossibility of the validation of the model is the difficulty to find two systems (read organisations) within the same environment and external interfaces, one willing to take the approach proposed by this research and the other ignoring it. Having done such a validation, one would also be limited to a conclusion that the model is valid (or invalid) only for the organisations that have been used in the validation.

There is however, an approach of validation that can be applied without suffering from the stringent requirements set for a real life experiment. This approach is called a thought experiment, which are experiments performed in the laboratory of the mind [Brown, 1991:1]. According to Brown [op cit], thought experiments are hard to explain beyond the metaphor just cited. Thought experiments which can be visualised, involve mental manipulations and are often (but not always) impossible to implement as real life experiments. Kuhn [1977:252] expands on the idea of thought experiments when he states that for a thought experiment to be effective, it must present a normal situation. A normal situation is when the person conducting the experiment feels well equipped by prior experience to handle the experiment. Nothing within the thought experiment must be entire unfamiliar or strange. To a large extent this implies that one has to have a good background or experience, as well as intuition about the subject of the thought experiment to be able to conduct the thought experiment.

Norton [in Brown, 1991:46] states that thought experiments are merely arguments; derivations from given premises. The information required for the thought experiment does not come from the reporting of new empirical data. The information should be non-controversial, elicited from information we already have by identifiable argument. Well known scientists who used thought experiments to great effect were Galileo, Einstein, Stevin, Heisenberg and Newton [Brown, 1991].

Given the above arguments, it seems appropriate to use a thought experiment for the validation of the generic integrated logistic support model. The thought experiment is based on the premises that all systems go through a life-cycle, that design should be a conscious effort and that organisations and products can be viewed as systems requiring both managerial and technical activities throughout its life-cycle.

## 9.3 Goldratt's thought experiment applied to an organisation as a system

Goldratt [1990:14-18] uses a thought experiment to derive generic operational measurements for an organisation. Based on the goal of a for-profit organisation, namely to make more money now as well as in the future, the thought experiment is conducted for a money-making machine. Thus the organisation's complexities are reduced to such a level where the essence of the organisation can be understood by analysing the money-making machine as a metaphor for an organisation. As durable products exist for a particular purpose, they can also be treated as money-making machines e.g. a manufacturer of motor vehicles buy an assembly robot (a product system) first and foremost to perform production activities but ultimately to help the organisation to make more money. Even in the event where a durable product is not bought to assist in making money, there still has to be a benefit which in the end can be equated to making more money. Three measurements are deductively defined for a money-making machine (i.e. the organisation or the durable product). These measurements are throughput or the money-making machine's ability to generate money (or benefits in the case of a not-for-profit system), inventory which indicates the amount of investment required to buy, own and operate the money-making machine, and operational expense which is associated with the cost of operations of the money-making machine. The formal definitions for the three measurements are the following [Goldratt, 1990:19, 23, 29]:

- Throughput is the rate at which the system generates money through sales and can be expressed as :

$$Throughput = Volume(Selling\ price - Variable\ cost) \tag{9.1}$$

  where variable cost refers to true variable cost.
- Inventory is all the money the system invests in purchasing things the system intends to sell. Inventory consists of all, raw material, work in process, finished goods, fixed assets and moveable assets. The goal is to make money, not to own assets. If assets do not make money, they should be sold.
- Operating expense is all the money the system spends in turning inventory into throughput and consist of all fixed costs, whether direct or indirect, that does not change with an increase or decrease in volume.

## 9.4 Using Goldratt's machine as the subject of the thought experiment to validate the generic model for integrated logistic support

The measurements of throughput, inventory and operational expense as defined by Goldratt in his thought experiment are in line with the measurements of systems (ability, availability and affordability) as defined in this thesis. Throughput relates to ability, while inventory and operational expense relate to affordability. The system measurement that is not directly addressed in the measurements of the money-making machine, is availability. However, if Goldratt's thought experiment is scrutinised, one would find the availability dimension when the throughput is considered in line with its definition as a function of time, i.e. a rate and thus availability. The rate also implies a lapse of time and thus the life-cycle approach. A further point on the life-cycle approach is that inventory relates to the investment required to obtain and operate the system, again indicating a lapse of time and therefore the life-cycle. Furthermore, operational expense relates to the cost of obtaining, starting up and operating the money making machine. Again, a lapse of time is suggested and thus the life-cycle is implied. Within cost of operation the cost of maintenance is also included. The same money-making machine in Goldratt's thought experiment can thus be used as a thought experiment to validate the model proposed by this research, applicable to both organisational and product systems, as all three the system measurements can be demonstrated to improve through this experiment.

However, not all systems have profit motives and to simplify the thought experiment, the thought experiment will be reduced to just a machine. The generic operational measurements are also applicable to non-profit organisations. In order to cater for non-profit organisations, the definition of throughput is changed from 'generating money through sales' to 'generating goal units'. The limiting of the thought experiment to a machine is valid, as all systems (now represented by the machine) are built for a purpose defined as goal units, and the measurements of ability, availability and affordability are still applicable. The thought experiment is thus used to demonstrate how the application of the principles and interactions of the integrated logistic support model to a machine over its life-cycle will improve the ability, availability and affordability and thus overall machine performance.

Using a machine as the subject of the thought experiment, does not reduce the thinking to the machine age of systems thinking (see § 4.3.1). System age thinking (see § 4.3.2) is still used as the machine is still viewed within its larger context (expansionism), it is goal seeking (teleology), and optimising a single part (e.g. ability) does not necessarily improve the system as a whole (synthetic thinking).

### 9.5 The structure of the thought experiment

As has been shown in the Chapter 5, all things are created twice. Covey [1992:99] states that “*you really have to make sure that the blueprint, the first creation, is really what you want, that you have thought everything through. Then you put it in bricks and mortar*.” Covey [1992:100] further argues the principle that all things are created twice by stating that the first creation can be either of conscious design or it can be left to chance. What is implied in Covey’s statement is that design should be a conscious effort followed by the physical construction. What he fails to address, but what follows naturally, is after the construction one needs to consciously manage and use (operate) what has been created, otherwise it will not fulfil its purpose.

As has been demonstrated in § 4.8.1, system (and thus machine) success is measured using the three measurements of ability, availability and affordability. If any one of these dimensions of success is not met, the machine cannot be successful in pursuing its goal. These measurements are to be considered during the design as a conscious effort to achieve all three measurements. The first measurement is concerned with the machine’s functional ability i.e. what the machine can do. Machines are designed and operated to achieve a specific purpose. If that purpose or goal cannot be achieved, the machine is useless. The second measurement is concerned with the machine’s availability to perform its intended function. A machine with excellent ability but no availability is also useless. The third measurement ensures that the machine is affordable i.e. the benefits derived from the machine are more than the associated cost.

In order to perform the thought experiment, the two integrated logistic support dimensions (introduced in § 4.6) of the machine are to be considered. They are the logistic subsystem, from here on referred to as the operational support, and the maintenance subsystem, from here on referred to as the maintenance support. The operational support and maintenance support of the machine are necessary for the ability, availability and affordability that will lead to overall system success. These relationships are shown in Figure 9.2. These two dimensions provide clarity on how good design decisions during the acquisition phase and the execution thereof during the operational phase, along with the management of the design and operational activities throughout the life-cycle will ensure improved ability, availability and influence affordability of the machine.

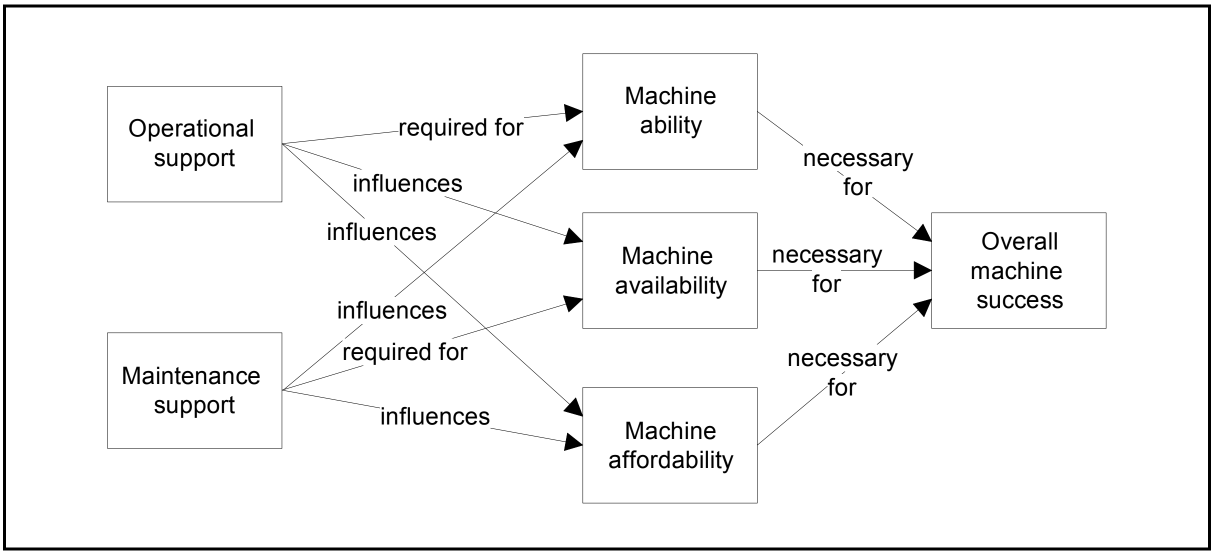


**Figure 9.2: The relationship between the two dimensions of integrated logistic support and the system measurements**

The operational support dimension deals with the operational requirements of the machine to perform its intended function. The first part of the thought experiment is conducted by viewing the design of a machine without considering the operational support required. This is then compared to when the design is a conscious effort where the principles of the integrated logistic support approach as proposed by the model for integrated logistic support are considered. This first part of the thought experiment is dealt with in § 9.6.

The maintenance support dimension deals with the maintenance requirements, derived from the interrelationships between the inherent design characteristics and its influence on the requirements for restoring and/or retaining the machine in an operable state. Thus the second part of the thought experiment will be conducted by viewing the design of a machine without considering the maintenance support required during its operational phase. This will then be compared to the design being a much more conscious effort where the principles of the integrated logistic support approach are considered. This second part of the thought experiment is dealt with in § 9.7.

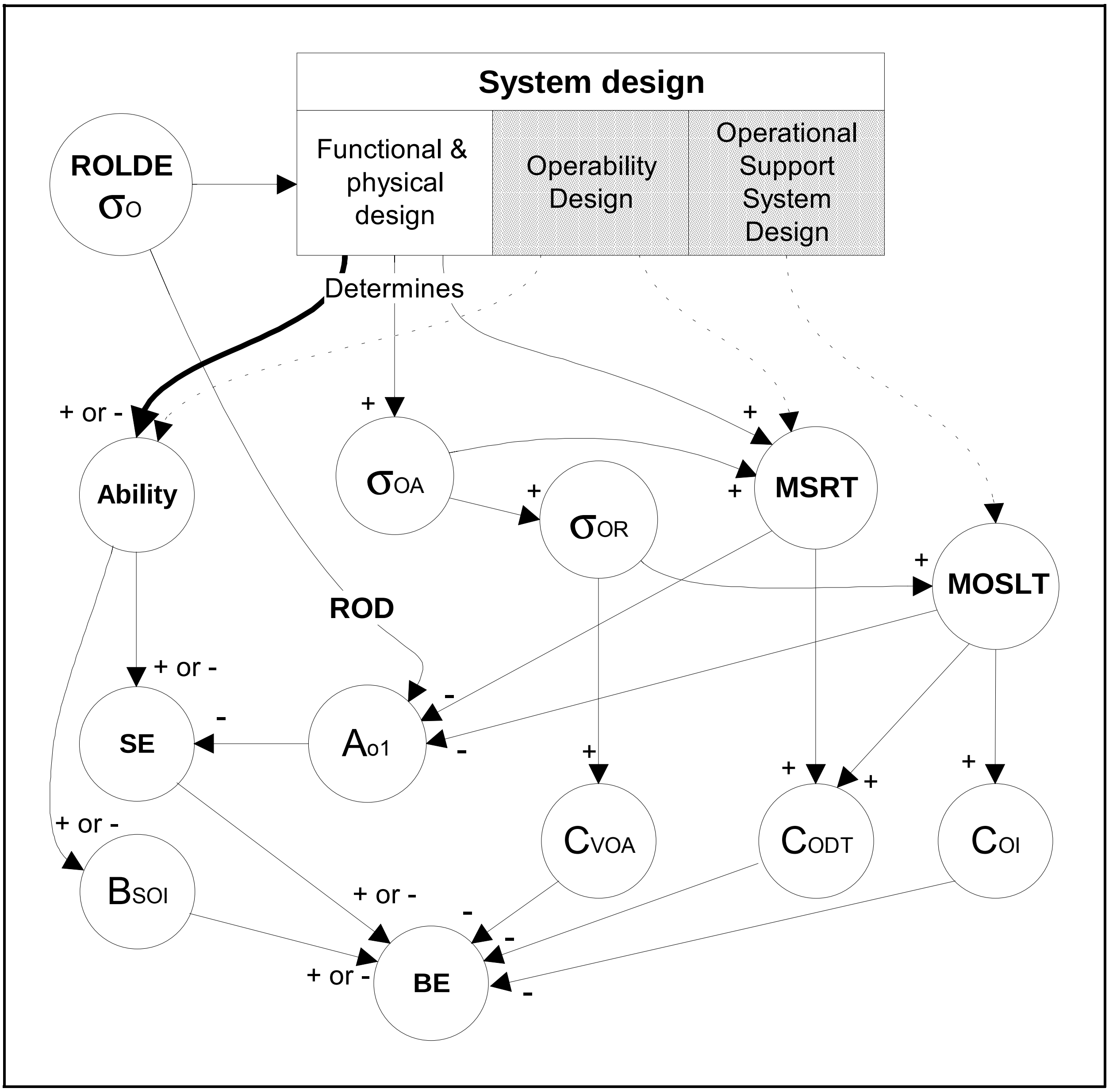
The thought experiment will be concluded by validating the management requirements as proposed by the model for integrated logistic support to ensure ability, availability and affordability of the machine during each of the life-cycle phases. This final part of the thought experiment is dealt with in § 9.8.

## 9.6 The operations support perspective of achieving machine success

When considering the design activities of a machine from an operational support perspective, it can be divided into different sets of activities, namely the functional and physical design, the operability design (the ease with which the machine can be operated) and the operational support system design (the business logistics). These design activities can be linked to the overall system measurements discussed in § 4.8.1, namely ability, availability and affordability of the machine, and the relationships between the design activities (operational perspective) and the overall system measurements can be identified and explained using implication diagrams.

### 9.6.1 Implication diagram tracing machine success when ignoring the approach to integrated logistic support

Figure 9.3 shows the complex interactions between the design activities (operational support perspective) and the overall measurements. It is an implication diagram tracing the effects of emphasising functional and physical (ability) design without consciously considering the operability design and the operational support system design. Ignoring these last two design activities more often than not increases the mean system replenishment time (MSRT) and the mean operational support lead time (MOSLT).



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|---|---|
| ROLDE | Required operations load, duration and environment. |
| ROD | Required operations duration. |
| MSRT | Mean system replenishment time. |
| MOSLT | Mean operational support lead time. |
| $A_{O1}$ | Operational availability (Operational support perspective). |
| BE | Benefit effectiveness. |

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|---|---|
| $\sigma_O$ | Operations demand rate. |
| $\sigma_{OA}$ | Operations activity demand rate. |
| $\sigma_{OR}$ | Operations resources demand rate. |
| $B_{SOI}$ | Benefits derived from the ability of the system of interest. |
| $C_{OI}$ | Cost of operations infrastructure. |
| $C_{VOA}$ | Variable cost of operations activities. |
| $C_{ODT}$ | Opportunity cost of operational down time. |

**Figure 9.3: Implication diagram focussing on ability only, ignoring operational operability design and operational support system design**

The dark line between functional/physical design and ability in Figure 9.3 indicates that the emphasis of design is on improving the machine's ability whereas the shaded areas indicate that the other design activities and their interfaces (dotted lines) with the measurements, are not getting any emphasis and are being ignored. This emphasis on functional and physical design causes the ability of the machine to improve. However, if consideration is not given to operability design, the ability of the machine may even decrease because of more complex man-machine interfaces, the inability of the human to operate and control the machine or poor ergonomic design. Emphasising ability design may cause an increase in ability, but at the same time cause a much bigger demand for operational activities ($\sigma_{OA}$) (e.g. increased power output for a Formula 1 Grand Prix car but higher fuel consumption, therefore more support activities to replenish the fuel). An increase in the demand for operations support activities immediately increases the demand for operational resources ($\sigma_{OR}$). Take note that the type of operation undertaken by the machine will determine which operational activities and resources will be required e.g. high flying reconnaissance versus take-off and landing training with the same aircraft.

Conceptually a machine's availability is expressed as the ratio of machine's available operational time divided by the total machine time. In order to explain this dimension of operational availability it is necessary to take the required operation duration (ROD) for the machine as the total machine time. From a machine user's perspective the machine is required to be available for the total duration of machine operation which implies 100% availability. The available time can however be interrupted by operational activities which are required to ensure operations, e.g. refueling and operator relief/changeover. This figure is expressed as the mean system replenishment time (MSRT) and reduces the available time for operation. Having the necessary operations support resources (fuel, fresh operator) available when needed depends on the support system and is expressed as the mean operational support lead time (MOSLT). This figure also reduces the available time for operation if the machine has to wait for operations support resources e.g. raw material required is not available. The operations support perspective allows the availability equation to be expressed as:

$$A_{o1} = \frac{ROD - MSRT - MOSLT}{ROD} \tag{9.2}$$

Regarding the affordability, there is a variable component which will cause a variable cost ($C_{VOA}$) associated with operations e.g. fuel or raw material required, which will increase with an increase in the demand rate for operational support resources ($\sigma_{OR}$).

The mean system replenishment time (MSRT) is influenced by two factors. The first factor is the frequency of operational activities required. The higher the frequency the more time is spent on doing operational activities (e.g. one pit stop vs two pit stops for a Formula 1 Grand Prix car). The second factor is the ease or difficulty of performing these operational activities. How short these times are depends heavily on integrating the physical design with the operation support system design e.g. the success of a Formula 1 Grand Prix car pit stop is determined by closely integrating the physical design of the car (design of wheel attachments and fuel tank/receptacle) and the design of the support resources (mechanics, jacks, tools, fuel replenishing equipment, spares).

An increase in the demand for operational resources will cause a bigger demand on the operation and support system that are to supply these resources. This bigger demand on the operations support system will lead to an increase in the mean operational support lead time (MOSLT). The bigger the load on the operational support system, the higher the cost of operational infrastructure ($C_{OI}$).

The combined effects of the increase in mean system replenishment time (MSRT) and the mean operational support lead time (MOSLT) will cause the operational availability ($A_{O1}$) to go down (refer to equation 9.2). Even though ability has gone up, it would only be luck if the decrease in availability balances out with the increase in ability when the system effectiveness is calculated (see equation 4.4). Considering the increase in all costs identified and an increase in overall ability, combined with a most probable drop in system effectiveness, the nett benefit calculation (see equation 4.7) will determine in the final instance the nett effect of the attempt to improve ability. Again, it will only be luck if the conflicts balance out. Thus it is concluded that integrated functional/physical, operability and operational support system design is imperative from an operational perspective in order to achieve overall system success.

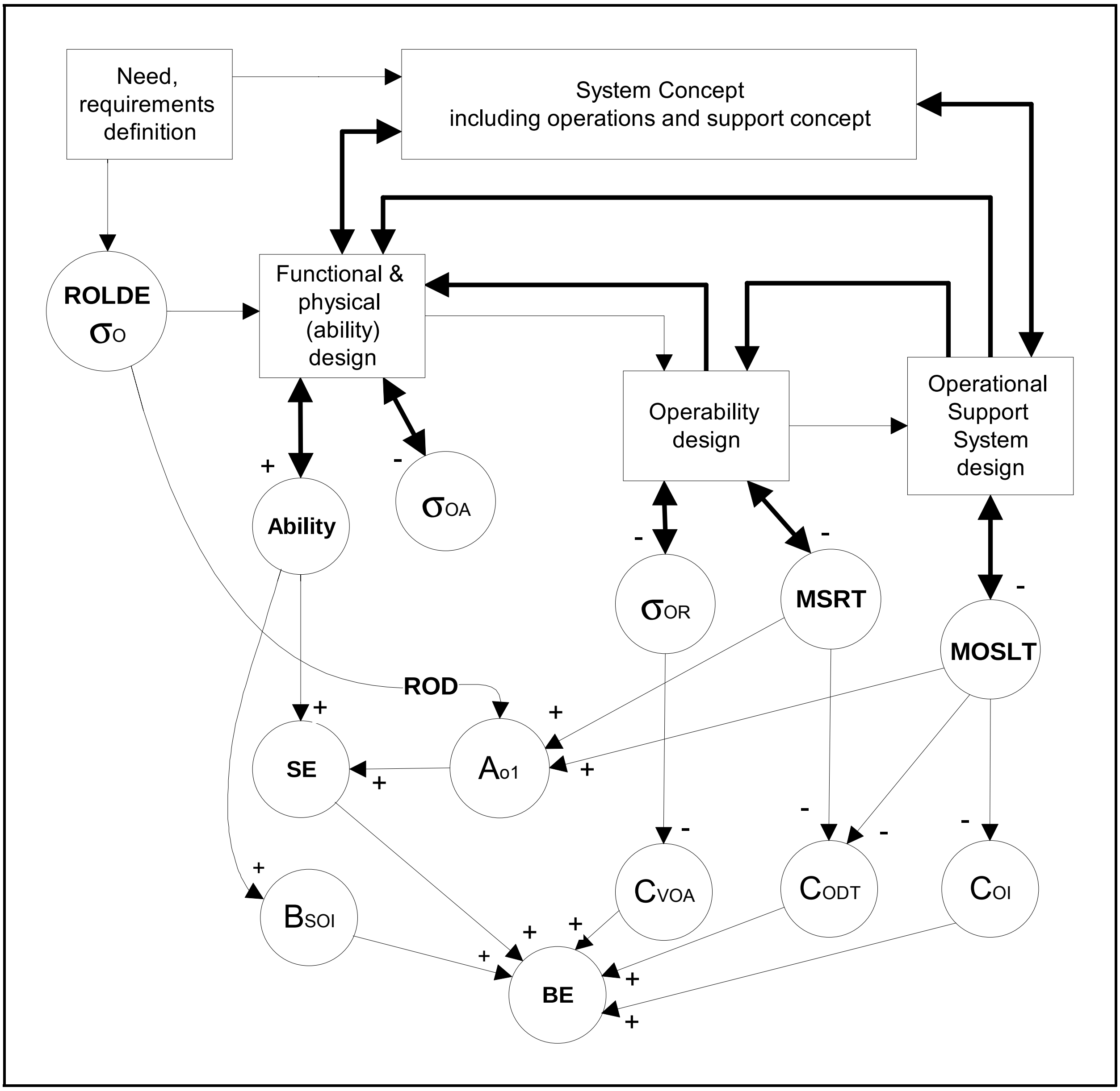
The operational support perspective leading to the achievement of overall system success is thus based on two premises. The first is that no system can truly be a closed system which implies that any system needs to be supported to perform its intended function otherwise it will (eventually) cease to function. Thus the support system must be of conscious design. The second premise is the design can be influenced to improve the man-machine interface and the operability characteristics of the system.

### 9.6.2 Implication diagram tracing system success when machine operability design and operational support system design is a conscious effort

Figure 9.4 provides a view of the integrated logistic support design activity as proposed by the model in Chapter 8. Thin lines indicate flow from one activity to another or cause-effect relationships. Dark lines indicate design influencing loops from one design activity to another or between a design activity and parameters that need to be improved.

Tracing the logic in Figure 9.4, the outcome of the functional and physical design activity is the ability of the design with its associated man-machine interface. The demand for operational activities ($\sigma_{OA}$) consists of two dimensions. The first dimension of operational demand relates to the people and resources directly interfacing with the machine in order to operate the machine. Factors to be considered when doing the functional and physical design with regards to the operating personnel and resources are the following:

- Operator skills and operator task complexity.
- Ease of machine operation and machine control.
- Consideration of operating environmental conditions.
- Ergonomics of the machine operator interface.
- Safety of operating personnel.
- Standardised operating procedures.
- Additional training requirements for operating personnel.



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| $C_{ODT}$ | Opportunity cost of operational down time. |

**Figure 9.4: Implication diagram of the generic approach to integrated logistic support (Operational support perspective)**

The second dimension of the demand for operations ($\sigma_{OA}$) consists of the personnel and resources required to provide operational support and keep the machine running. These activities are not to be confused with maintenance activities. In some cases there is no distinction between the personnel and resources required for operation and those personnel and resources required for operational support (e.g. the operator of a tractor on a farm will, apart from ploughing, also replenish the fuel) while in other cases there is a clear distinction between the personnel and resources required for operation and operational support (e.g. a racing driver responsible for operation and his pit crew responsible for operational support). The aim of functional/ physical design is thus to increase the ability by taking into consideration the man-machine interface by reducing the amount of operator activity while at the same time reduce the demand for operational support activities. This approach is not an attempt to eliminate people from systems. The rule of thumb as far as this author is concerned is to have operators do those tasks which are within human capability and judgement, and where the performance of the human in executing the task is superior to that of equipment or technology. Factors to be considered when doing the functional and physical design with regard to the operating support personnel and resources are the following:

- Operational support skills and operational support task complexity.
- Ease of machine operational support and operational support system control.
- Consideration of operational support environmental conditions.
- Ergonomics of the machine operational support interface.
- Safety of operational support personnel.
- Standardised operational support procedures.
- Additional training requirements for operational support personnel.

The demand for operational activities ($\sigma_{OA}$) is heavily influenced by the required operational load, operational duration and operational environment. The frequency of demand for operations ($\sigma_O$) will also have a major influence on the demand for operational activities ($\sigma_{OA}$), especially if the machine has major start-up and shut down operational support requirements e.g. a steel mill.

The operability design uses input provided by the ability design to analyse the physical characteristics of the design along with the man-machine interfaces to ensure that the operational resources (operating and support) can be minimised as much as possible without affecting performance. Operability design consist of two dimensions. Firstly it is concerned with the design of the operational activities, both the operations tasks and the support tasks. Secondly it is concerned with the identification of operational resources required to perform those tasks. Feedback is provided to improve the design in order to have fewer (but more effective and efficient) operational tasks and less operational resources. Feedback is also provided to ensure that the interfaces between the design and the support system resources are compatible to ensure the lowest possible mean system replenishment time (MSRT). The less the demand for operational resources ($\sigma_{OR}$), the less the variable cost of operations activities ($C_{VOA}$).

The operational support system design uses input obtained from the operability design to ensure availability of all operational resources. The operational support system design must be done considering the operability (task) design and the demand rate and quantities for operational resources. The operational support system design has as its aim to provide the machine with the required resources for operations, both the operations dimension and the support dimension. This operational support system is what is commonly referred to as the business logistics or supply chain of the system. The unit of measure is the mean operational support lead time (MOSLT) and is calculated from the point in time where the machine is down due to a requirement for operational support, to the point in time where the resources are available to do the support. The actual support task, termed replenishment, will not be included in the mean operational support lead time (MOSLT); it is accounted for by the mean system replenishment time (MSRT). The operational support system design consists of all the managerial and technical designs to ensure that the operations support can take place, including activities like warehouse design, support inventory management systems, and selection, appointment, training and development of operating personnel. The operational support system can be a totally new system, or it can be a modification to the host system’s existing operational support system. Failure to consciously design the operational support system of the machine will cause major disruptions during the operational and support phase.

The reduction of both the mean operational support lead time (MOSLT) and the mean system replenishment time (MSRT) will increase the operational availability ($A_{O1}$) of the machine (refer to Equation 9.2). The overall operational support system design should thus ensure that the mean operational support lead time (MOSLT) be zero from an operations point of view. This should be done without an excessive increase in the cost of infrastructure ($C_{OI}$), which during the operational phase will be considered a fixed cost. This implies that the operational support system must function in such a way that operations are not stopped during a required period of operation due to shortage of operational resources. The only way to achieve this, is to have a properly designed operational support infrastructure that considers the operational requirements. For more information on the principles of a distribution system design see Goldratt [1999]. It can be argued that the cost of infrastructure ($C_{OI}$) will rise dramatically in order to decrease the mean operational support lead time (MOSLT), as redundancy in the support system is required to achieve a low mean operational support lead time. However, it has been proven that the mean lead time of any operation can be reduced by not investing in huge amounts of redundancy, but to have high availability of resources and by processing/ordering in small lots more often [Goldratt, 1986 and 1999], which allows the total investment or cost of infrastructure ($C_{OI}$) to decrease. The approach is similar to the JIT philosophy of inventory reduction [Cheng and Podolsky, 1993:44-45].

The combined reduction of mean operational support lead time (MOSLT) and the mean system replenishment time (MSRT) will lead to a reduction in the cost of machine operational downtime ($C_{ODT}$). From the above it follows that the operational support system must be designed to use some form of buffer to make operational support lead time appear to be zero from an operational point of view. The bigger the buffer is, the higher the cost of operational infrastructure ($C_{OI}$), but at the same time the lower the cost of operational down time ($C_{ODT}$) due to higher availability of operational resources. As has been demonstrated in the previous paragraph, the cost of operational infrastructure ($C_{OI}$) need not increase, provided that the buffer within the operational support system is designed and managed properly. The design of this buffer should be based on the principle of smaller lots more often which will result in shorter overall lead times and reduced inventory.

Even though ability design and operability design are shown as separate blocks, the approach to be followed is to integrate these two design actions into one. These two design activities are interlinked through the design and overall design characteristics. The designer should thus know what the impact of any design decision is on the operability of the system and be able to trace the effects of the design decision down to the benefit effectiveness (BE) of the system of interest.

Figure 9.4 can thus be used to trace the effect of conscious integrated logistic support design decisions on the operability of the machine and the operational support system. It is not claimed that it represents a complete set of interdependent system characteristics, but it is used to convey the idea of the integrated nature of systems and how an integrated logistic support approach can improve the system performance.

## 9.7 The maintenance support perspective of achieving system success

When considering the design activities of a system from a maintenance perspective, it can be divided into different sets of activities, namely the functional and physical design, the reliability design, the maintainability design and the maintenance system design. These system design activities can be linked to the overall system measurements discussed in § 4.8.1, namely ability, availability and affordability, and the relationships between the system design activities (maintenance support perspective) and the overall system measurements can be identified and explained.

### 9.7.1 Implication diagram tracing system success when ignoring the approach to integrated logistic support

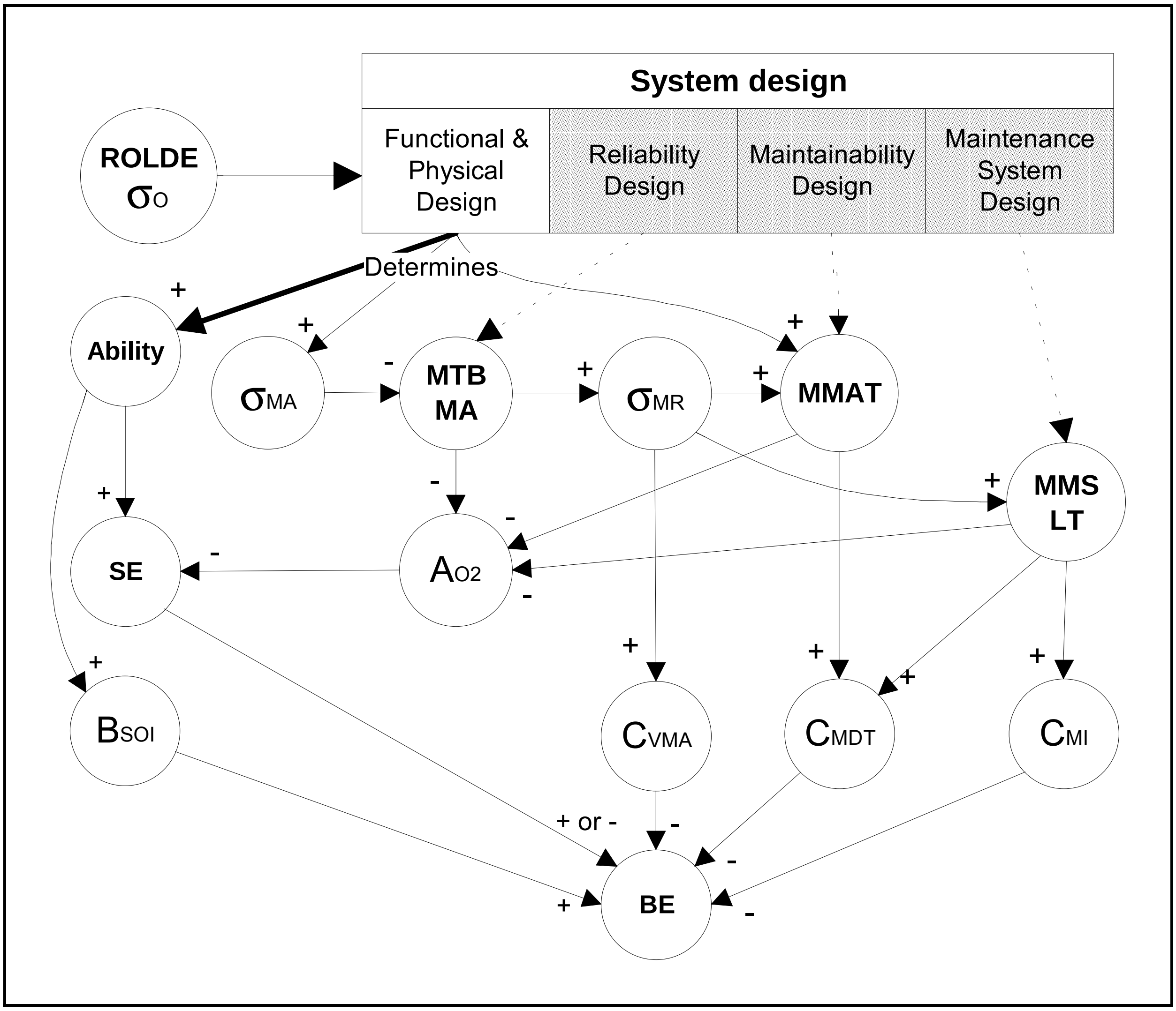
Figure 9.5 shows the complex interactions between the system design activities (maintenance support perspective) and the overall system measurements. Figure 9.5 is an implication diagram tracing the effects of focussing on functional and physical (ability) design without consciously considering the reliability design, the maintainability design and the maintenance system design. Ignoring these design activities more often than not decreases the reliability figure (mean time between maintenance actions - MTBMA) and increases the maintainability figures (mean maintenance activity time - MMAT and mean maintenance support lead time - MMSLT), resulting in a lower availability.

The dark line between functional/physical design and ability in Figure 9.5 indicates the emphasis in design is on improving the ability whereas the shaded blocks indicate that the other design activities and their interfaces (dotted lines) with the system measurements are not getting any emphasis and are being ignored. When the emphasis is placed on the functional and physical design it will cause the ability to improve. If consideration is not given to reliability design, the demand for maintenance activities ($\sigma_{MA}$) will increase (due to more possible failure modes, more parts, more complex interfaces), which will result in the mean time between maintenance activities (MTBMA) to decrease. This implies more maintenance activities, thus an increase in the demand for maintenance resources ($\sigma_{MR}$).

It has been shown previously in this thesis that availability is a function of both reliability and maintainability (see Equation 4.3). The reliability figure is expressed as the mean time between maintenance activities (MTBMA), implying the inclusion of both preventive and corrective maintenance activities in the availability figure. Maintainability is expressed as the sum of the mean maintenance activity time (MMAT) and the mean maintenance support lead time (MMSLT). The second dimension (the maintenance perspective) of operational availability ($A_{O2}$) can thus be expressed in the following equation:

$$A_{O2} = \frac{MTBMA}{MTBMA + MMAT + MMSLT} \tag{9.2}$$

Emphasising the functional and physical design more often than not increases the mean maintenance activity time (MMAT). This is because factors like accessibility, ease of fault finding, use of standard components and other maintainability issues are ignored or forgotten in favour of improving the ability of the design. The increase in the demand rate for maintenance resources ($\sigma_{MR}$) and the increase in the mean maintenance activity time (MMAT) both cause a bigger demand on the maintenance system (whose design is also ignored) with a resultant increase in the mean maintenance support lead time (MMSLT).



| | |
|---|---|
| ROLDE | Required operations load, duration and environment. |
| MTBMA | Mean time between maintenance activities. |
| MMAT | Mean maintenance activity time for both preventive and corrective maintenance. |
| MMSLT | Mean maintenance support lead time. |
| SE | System effectiveness. |
| BE | Benefit effectiveness. |

| | |
|---|---|
| $A_{O1}$ | Operational availability (Maintenance perspective). |
| $\sigma_O$ | Operations demand rate. |
| $\sigma_{MA}$ | Maintenance activity demand rate. |
| $\sigma_{MR}$ | Maintenance resources demand rate. |
| $B_{SOI}$ | Benefits derived from the ability of the system of interest. |
| $C_{VMA}$ | Variable cost of maintenance activities. |
| $C_{MDT}$ | Opportunity cost of maintenance down time. |
| $C_{MI}$ | Cost of maintenance infrastructure. |

**Figure 9.5: Implication diagram focussing on ability only, ignoring reliability, maintainability and maintenance system design**

The combined effects of the decrease in the mean time between maintenance activities (MTBMA), and the increase in both the mean maintenance activity time (MMAT) and the mean maintenance support lead time (MMSLT), will cause the operational availability to go down (refer to Equation 9.2). Even though the ability has gone up, it would be luck if the decrease in availability balances out with the increase in ability when the system effectiveness is calculated (see Equation 4.4). It is also clear that the increased demand rate for maintenance resources ($\sigma_{MR}$) will have the variable cost of maintenance activities ($C_{VMA}$) increase (more spares, consumables), and the increase in mean maintenance lead time (MMLT) will cause the cost of maintenance infrastructure ($C_{MI}$) to increase (more facilities, personnel, warehouses, maintenance management systems). The cost of maintenance downtime ($C_{MDT}$) will increase due to the increase in mean maintenance activity time (MMAT) and the increase in mean maintenance support lead time (MMSLT).

The nett effect on the system will be seen in the benefit effectiveness calculation (see equation 4.7). Even if system effectiveness does go up, which is not very likely because of decreased availability, and a positive effect is seen on the benefits delivered by the system because of the increase in ability, the benefit effectiveness will probably go down because of the effect of the increase in cost. Again, an increase in net benefit effectiveness will be luck if the increase in ability is pursued at the expense of reliability, maintainability and the maintenance system design.

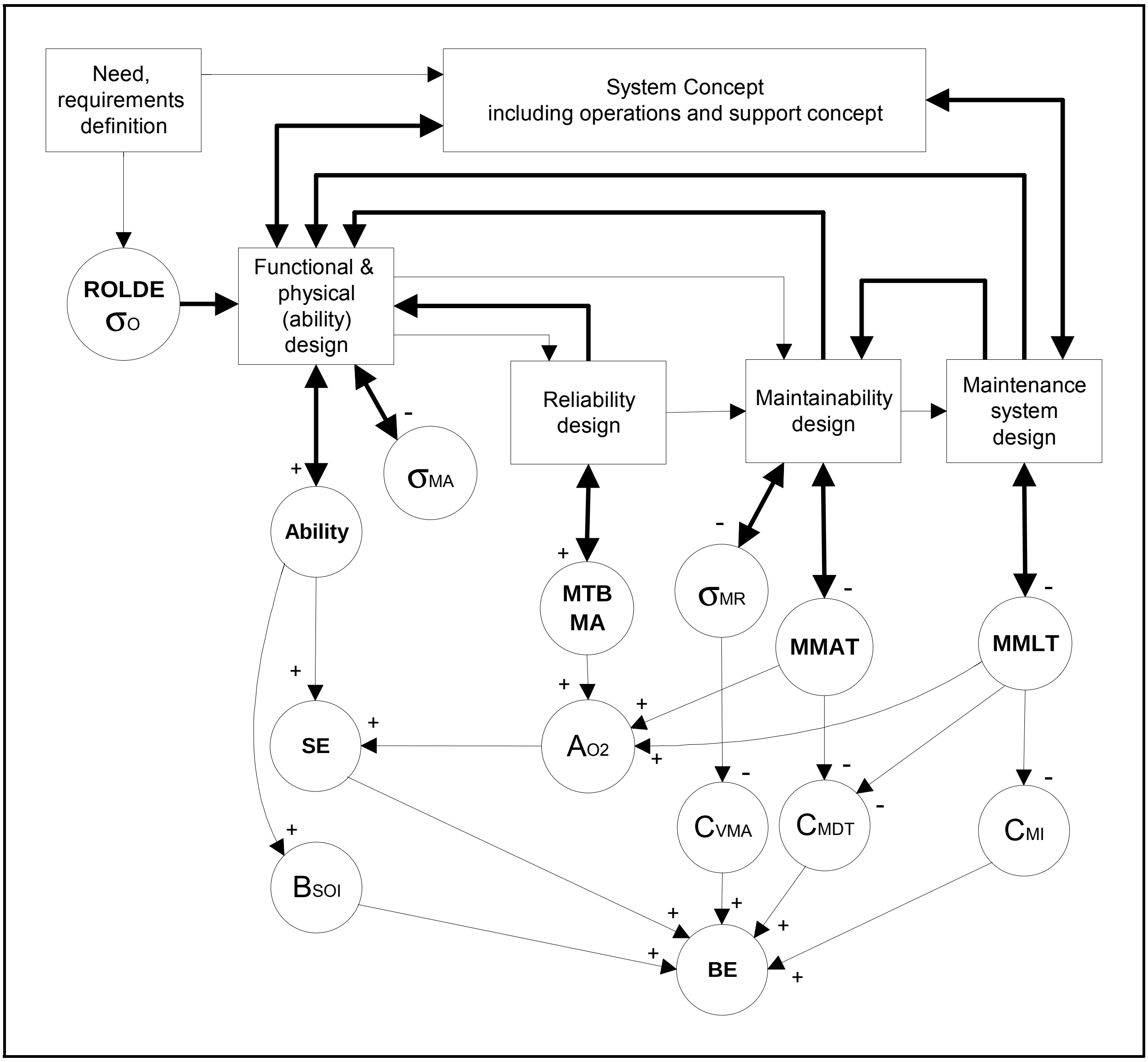
It can thus be concluded that designs cannot be optimised independently, which means that design trade-offs are to be made between the different design activities to get a better overall design [M'Pherson, 1981:574]. From the maintenance perspective, the design activities required to achieve overall system success are the reliability design, maintainability design and the maintenance system design. On the higher system level these design activities are interlinked by the operations and support concept (which was discussed in § 8.3.1.3), which allows the different design activities to make use of each other's output within a common framework, but also allows feedback or design influencing. This integrated approach to logistic support design takes into consideration not only the performance characteristics of the design (ability), but the overall system performance and improving the overall system outcome expressed as the nett benefit of the system.

The maintenance perspective leading to the achievement of overall system performance is based on three premises. The first premise is that systems are not perfect and the mean time between failure is not infinitely large, thus maintenance activities - both preventive and corrective - are required. The second premise of the maintenance perspective is that a design can be influenced or changed to improve the inherent reliability and maintainability characteristics of the design. The third premise is that the maintenance support system has to be properly designed in order to provide the maintenance support to achieve the ability, availability and affordability requirements of the system.

### 9.7.2 Implication diagram tracing the system success when system reliability, maintainability and maintenance system design is a conscious effort

Figure 9.6 provides a view of the integrated design activities proposed by the model in Chapter 8. Dark lines indicate design influencing feedback from one design activity to another or between a design activity and a parameter that needs improvement.

Tracing the logic in Figure 9.6, the outcome of functional and physical design is the ability of the design as well as the demand rate for maintenance activities ($\sigma_{MA}$). The aim is improving the ability but at the same time decreasing the demand for maintenance activities ($\sigma_{MA}$). When designing, designers should consider the different modes of operation of the concept under consideration, expressed as the required operation load and duration, the environment in which the operation will take place (ROLDE), as well as the demand rate for operations ($\sigma_O$). These two (ROLDE and $\sigma_O$) in combination will have a major influence on the demand rate for maintenance activities ($\sigma_{MA}$). A high operational demand rate implies many stop-start situations, which may cause more wear and tear on the system, whereas a low demand rate may have less wear and tear due to fewer stop-starts. Long durations of operations may require high reliability with few start-ups and shut-downs, such as a satellite system, but at the same time require good maintainability to minimise down-time as much as possible. Using a system in a controlled environment, such as an electronic system in a clean room with well trained operators, as opposed to a military system in harsh environmental and battle conditions, will have a major influence



| | |
|---|---|
| ROLDE | Required operations load, duration and environment. |
| MTBMA | Mean time between maintenance activities. |
| MMAT | Mean maintenance activity time for both preventive and corrective maintenance. |
| MMLT | Mean maintenance lead time. |
| SE | System effectiveness. |
| BE | Benefit effectiveness. |

| | |
|---|---|
| $A_{O1}$ | Operational availability (Maintenance perspective). |
| $\sigma_O$ | Operations demand rate. |
| $\sigma_{MA}$ | Maintenance activity demand rate. |
| $\sigma_{MR}$ | Maintenance resources demand rate. |
| $B_{SOI}$ | Benefits derived from the ability of the system of interest. |
| $C_{VMA}$ | Variable cost of maintenance activities. |
| $C_{MDT}$ | Opportunity cost of maintenance down time. |
| $C_{MI}$ | Cost of maintenance infrastructure. |

**Figure 9.6: Implication diagram of the generic approach to integrated logistic support (Maintenance support perspective)**

on the probability of experiencing breakdowns. The intensity of the load (running at full capability or at half load) also influences the demand for maintenance activities ($\sigma_{MA}$).

Thus the demand for maintenance activities ($\sigma_{MA}$) is a direct result of the inherent failure modes of the design. This means that the inherent reliability of the design is a direct consequence of ability design, influenced by the required operation load, duration and environment (ROLDE) and demand for operations ($\sigma_{O}$), and expressed as mean time between maintenance activities (MTBMA). It is therefore imperative that reliability design takes place as a conscious interactive design action order to get satisfactory performance ***and*** reliability of the design. Reliability design receives its input from the ability design and takes into consideration how the design can fail, the frequency of failures (the demand rate for maintenance activities), and the effects and seriousness of the failures.

If the ability is satisfactory, but the reliability and/or safety is not, feedback should be given to the ability design to improve the design from a reliability and/or safety point of view. Design feedback from a safety point of view, aims to change the design to eliminate a certain failure mode to make the design more safe, or to add safety measures to reduce the probability of that safety failure from occurring. Design feedback from a reliability point of view aims to change the design in order to increase the reliability by reducing the demand rate for maintenance activities ($\sigma_{MA}$), thus increasing the mean time between maintenance activities (MTMBA). Improved reliability also implies less maintenance requirements resulting indirectly in a lower life-cycle cost. The design changes implemented to improve safety and reliability may cause the performance to either suffer or improve. In the final instance, the design has to strike a balance between performance, safety, and reliability to get the best overall system outcome within the available time and cost constraints of the development phase. The final outcome of reliability design is the mean time between maintenance activities (MTBMA), which implies both preventive and corrective maintenance that will be required by the system during the operational phase.

The data generated by the ability design and the reliability design serves as input to maintainability design. The maintainability design analyses the physical characteristics of the design, taking into consideration the nature and frequency of maintenance required to restore system availability (corrective maintenance), as well as the nature and frequency of the need to maintain system availability (preventive maintenance).

Maintainability design consists of three dimensions. The first dimension is concerned with the potential hazards and unsafe conditions of maintenance caused by the ability design. If, for instance, a high pressure vessel can be opened for maintenance without forcing the maintainer to bleed the pressure first, the design is inherently unsafe from a maintenance perspective. Thus, design feedback is given to improve the design from a maintenance safety point of view. Inherent design characteristics that cause unsafe maintenance conditions are identified to change the design to eliminate those unsafe maintenance conditions.

The second dimension of maintainability design is concerned with the inherent maintainability of the design which determines the amount of time required to restore the system to its original ability after a failure has taken place, or the time taken to retain it in its original state, provided all maintenance resources are available. This dimension is expressed as the mean maintenance activity time (MMAT). The maintainability design action is therefore concerned with the inherent maintainability design characteristics of the design and feedback is given to ability design in order to improve the design from a maintainability point of view. Similar to reliability influence, such design influence may cause the performance either to improve or suffer. Typical inherent maintainability characteristics that can be influenced to reduce the mean maintenance activity time (MMAT) are:

- Accessibility to components and sub-systems..
- Ease of performing maintenance activities, including ergonomics.
- Use of standard connectors.
- Ease of failure detection and failure isolation.
- Standardisation and rationalisation.

A reduction in the mean maintenance activity time (MMAT - the time required to perform the physical maintenance activity) will have a positive influence on the operational availability of the system. The mean maintenance activity time (MMAT) will partially determine the cost of maintenance downtime ($C_{MDT}$). The other component that determines the cost of maintenance downtime is the mean maintenance support lead time (MMSLT) which will be discussed in more detail as part of the support infrastructure of the maintenance system.

The third dimension of maintainability design is concerned with the identification of maintenance resources required to perform the maintenance activity and expressed as the demand for maintenance resources ($\sigma_{MR}$). The maintenance resources fall into two categories, namely a variable part and a fixed part.

The first maintenance resource category consists of the variable part e.g. consumables and spares, whose quantities are determined by the inherent maintainability of the design (e.g. using quick release fasteners for an attachment versus using four screws for the same attachment) and the nature of the maintenance activity design (e.g. modular replacement vs component replacement). Many times these quantities of spares or consumables will be required every time the maintenance activity is performed. Sometimes these quantities are based on a probability distribution or averages e.g. in 50% of the cases where a wheel repair is to be done a new tire is required. The demand rate for maintenance activities and the demand rate for the variable component of the maintenance resources will therefore result in a certain variable cost for maintenance activities ($C_{VMA}$).

The second category of the maintenance requirements consists of the support infrastructure or the fixed component of the maintenance system. The quantities of these maintenance resources are normally not discrete for the maintenance activity and is expressed as a percentage of a required resource’s time that is needed to effect the maintenance activity. Examples of this fixed component are the percentage of one man-month required to perform a wheel repair, and the percentage of facility capacity that is required for the same maintenance activity. These resource capacities are normally fixed in the short to medium term, and many times also in the long term. It is much more difficult to adjust these resource levels once the system is in operation as opposed to adjusting the variable component of the maintenance resources. This fixed component also comprises the overall management system of the support system, which as a result determines the mean maintenance support lead time (MMSLT). This lead time includes all delays, technical and managerial, from the point in time where the system is down due to a failure or requiring preventive maintenance, to the point in time where the system is functional once more, the actual maintenance time excluded. The actual maintenance time is accounted for by the mean maintenance activity time (MMAT). Therefore, the resources considered to be the fixed component determine the cost of the maintenance infrastructure ($C_{MI}$) of the system, indirectly influenced by the demand rate for maintenance activities ($\sigma_{MA}$) and the demand rate for maintenance resources ($\sigma_{MR}$). It should be obvious that the mean maintenance support lead time (MMSLT) and the mean maintenance activity time (MMAT) combined are the major factors determining the cost of maintenance downtime ($C_{MDT}$).

In comparing the impact of the mean maintenance activity time (MMAT) and the maintenance lead time (MLT) on operational availability ($A_{O2}$ - see Equation 9.2), it is clear that the overall downtime should be mostly dependent on the mean maintenance activity time (MMAT). Therefore the design of the overall maintenance system plays a major role in the operational availability of the system of interest to ensure that no maintenance activity is delayed because maintenance resources are not available.

Even though ability design, reliability design and maintainability design are shown as separate blocks in Figure 9.6, it ultimately consists of one action namely design, which are interlinked through different design parameters and characteristics. The arrows from ability design leading to reliability design and maintainability design highlights this point. By doing ability design, the reliability and maintainability characteristics are implicated, thus what is required from the designer is to know the impact of any design decision on safety, reliability, maintainability and eventually maintenance cost. Therefore the design action should allow all dimensions, performance, reliability, maintainability and resultant cost to be considered at the same time to get the best design possible from an ability, availability and affordability point of view. It also has to be brought in line with the end goal of the system, a figure which is indicated by the benefits of the system of interest ($B_{SOI}$) that are to be delivered. In the final instance, the benefit effectiveness (BE) integrates ability, availability and affordability into one figure.

Figure 9.6 can thus be used to trace the impact design decisions will have on the different maintenance parameters of the system when the integrated approach to logistic support is used. It is not intended to provide a complete set of interdependent system characteristics (for example the cost of the design actions are not included), but can be used to illustrate how interdependent system and design characteristics are and how the generic approach to integrated logistic support influence can be used to influence the ability, availability and affordability of the system.

## 9.8. The management perspective of achieving machine success

To understand the importance of managing the structured, integrated approach that considers all relevant characteristics of the design in order to achieve an able, available and affordable system, a further thought experiment can be conducted to see what the expected effects are if proper management focus is directed towards each phase of the life-cycle. Without going into the same amount of detail as in the previous thought experiment, it is still possible to conduct the experiment without too much effort.

Not all phases of the life-cycle are managed in the same way as each life-cycle phase has a different objective and requires different methodologies and techniques. The main premise, however, is that people normally do what they like best. When people have to choose between filling out their tax returns as opposed to taking a trip to the beach, most people will choose the latter. When an operations manager of our machine have to choose between production and doing maintenance, he will most probably choose production, as production time is a much more favourable measurement than time spent on maintenance. Similarly designers would much rather spend time designing new features and improved ability than analysing possible failure modes to design remedies or maintenance procedures for that. Thus if one wants anybody who designs, operates or maintains the system to do what is good for the system as a whole, and not only do the things they like, the only remedy is for management to plan, organise, direct and control all the activities required for successful machine operation, even those activities people normally despise. Thus, all measurements must be considered by management at the same time.

Within the acquisition phase, management has to look after those design activities ensuring full integration between ability, operability and operational support system design, as well as integration between ability, reliability, maintainability and maintenance support system design. Consideration for safety is naturally part of both the operational support and maintenance support perspectives and should also be managed as such.

Within the construction phase, management has to ensure that not only the machine is built, but also that the support system is put into place from both the operational and maintenance point of view to ensure that operations can take place at the time of commissioning the machine, but at the same time handling any breakdown of the machine by either preventing the failure before occurrence or correcting the failure after its occurrence. The overall operational support system and the maintenance support system have to be managed as well.

The same logic can be followed for the management of the recycling, waste disposal and phasing out of the machine. It can thus be concluded that without the management activities that change focus as demanded by the changing requirements of the technical activities of each phase, and integrating all the different aspects that will make for a good system, the technical activities can never achieve the machine's desired ability, availability and affordability requirements. If one chooses to ignore these management activities, very little will be done on the logistic support system with a resultant negative effect on the overall measurements of the machine, especially availability and affordability.

## 9.9 Chapter summary

When a model is constructed, it should also be validated to the extent possible. Not all models can be validated using empirical data. Conceptual models such as the one proposed in Chapter 8, can be validated using a thought experiment. A thought experiment is an experiment of the mind, where the implications and consequences of applying or not applying the model are thought through in a structured manner. The techniques used in validating the model proposed by this research is implication diagrams.

Implication diagrams have been used to predict the outcome on system measurements when the technical dimension of the model describing the approach to integrated logistic support is applied or ignored. For both the operational support and the maintenance support, one can expect to have much better system performance if the model is applied to the development and operational phases of the system life-cycle. In the case where the model is ignored and functional design is done at the expense of operational and maintenance support design, one can expect the ability to improve but have severe problems with availability and affordability of the system.

The management dimension described in the model for integrated logistic support is also required to ensure that the technical dimension is executed in a proper way, resulting in an overall improvement of the system measurements. Not properly managing the technical activities will cause a regression of the system measurements.