

# Improving Rock Climbing Safety using a Systems Engineering Approach

## ENGN2225- Systems Engineering and Design, Portfolio

### Abstract

This portfolio outlines an application of Systems Engineering methods to the sport of Rock climbing. The report outlines an organized, logical analysis of the system that is involved in making this sport safe and aims to improve the system as a whole through this analysis. Steps taken include system scoping, requirements engineering, system function definition, subsystem integration and system attributes which contribute toward a final concept. Two recommendations are made, one being a bouldering mat which incorporates the transportation of other equipment, the other being complete, standardised bolting protocols. These concepts are then verified against the design criteria and evaluated.

**1.0 System scoping:** A systematic way of establishing the boundaries of the project and focusing the design problem to an attainable goal. The project focuses on Lead Climbing.

**2.0 Requirements engineering:** Establishing the true requirements of climbers, and what they search for in a climbing safety system

**2.1 Pairwise Analysis:** Establishing safety, ease of use and durability as primary design goals

**2.2 Design Requirements and Technical Performance Measures:** Specifying the design requirements into attainable engineering parameters.

**2.3 House of Quality:** Identifying the trade-offs between safety and functionality/ cost and the need for a whole-of-systems approach to the problem, rather than a component approach.

**3.0 System Function Definition:** Establishing concepts and system processes.

**3.1 Concept Generation and Classification:** Identifying possible and existing solutions on a component level and taking these to a subsystem level.

**3.2 Functional Flow Block Diagrams:** Analysing the climbing process and identifying the most common causes of injury. As the process itself cannot be changed, the system can be modified to add functional steps to mitigate injury.

**4.0 Subsystem integration:** The development of new subsystems: The groundfall protection subsystem and the equipment transportation subsystem and identifying potential changes in the relationships of the subsystems through a Functional Block Diagram

**5.0 System Attributes:** Identifying modifications and procedures to be incorporated into the system to improve safety via an attributes cascade.

**6.0 Validation and Evaluation:** Determining the viability and efficacy of the proposed system.

**6.1 Design Validation:** Validating the incorporation of subsystems as improvements against the design criteria using specific testing methodologies.

**6.2 Evaluation:** Evaluating competing systems and component based solutions to improving safety.

## Introduction

In this report, a systems engineering approach is being used to analyse the system that revolves around rock climbing as an outdoor sport. The aim of this portfolio is to outline how this process was used to develop a novel method of improving safety for rock climbers. The approach is one of thorough analysis. Systems engineering involves looking at problems in terms of the overall system in which they exist, and how changes to that system can improve design outcomes. In this report there is a deliberate attempt to reduce the emphasis on specifics of design, and to change the focus to analysis and modification of the existing system which is used by rock climbers and has been used for many years. Many system approach tools are used as a method to understand the system as a whole and to identify where a subsystem could be altered, system interactions could be modified or a new subsystem could be integrated. This concept is then verified and evaluated.

It should be noted that the existing system that is used by rock climbers was likely never “designed” but rather was born out of trial and error, tradition and improvisation. The nature of the sport must still be maintained. In this report, the “clients” of interest were represented via a survey of the opinions of a group of experienced rock climbers from the Australian National University Mountaineering Club (ANUMC). (Lengyel et al. 2014)

## Background

Rock climbing is widely renowned as an adventure sport of significant danger and exhilaration. This in mind, very few people in the general public have an understanding of the true risks and challenges of this sport.

This report considers the system which is focused on “Lead Climbing”. Lead climbing is a common form of outdoor climbing which requires two people; the climber, and their belayer. In lead climbing, the climber ties their rope to their harness, such that as they climb, they take an end of the rope up the rock with them. During this process, “Protection” is added to the rock while they climb which allows the climber to arrest a fall with help from the “Belayer” who controls the movement of the rope using a belay device. This is illustrated in figure 1.

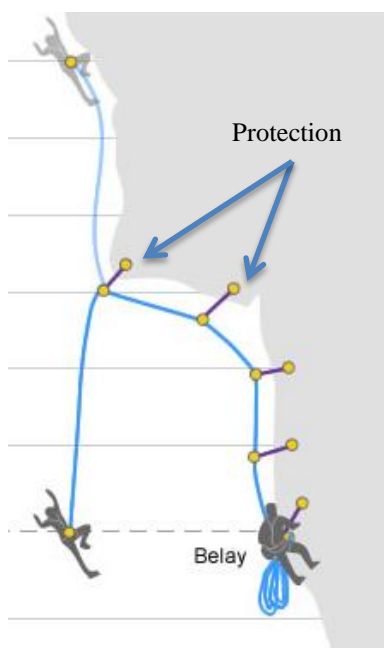


Figure 1 Diagram illustrating a Lead Climbing fall. (Ropebook, 2012)

Amongst experienced rock climbers, lead climbing falls are very common. This can vary from falls of 1-2m in length, or can involve falls of greater than 10m. Injuries as a result of this can be very severe in nature. In the most part however, injuries do not occur, as climbers do not collide with the ground or rock at great velocity. Statistical studies of severe (requiring professional medical treatment) rock climbing injuries have established that lead climbers represent the largest portion of those injured during outdoor roped climbing (30.5%) and 21.5% of fatalities (behind unroped climbing (39%)). Within roped climbing, lead falls are the cause of the highest proportion of incidents (39%). The most common injuries amongst climbers are lower extremity injuries (29.5%-46.4%). This is normally a result of falling when less than 3m off the ground, onto rough or uneven surfaces, or from large lead falls with incorrect technique. Rock climbing shoes generally do not offer support of the ankle or protection to the feet, therefore meaning these injuries can be quite severe; fractures and breaks being likely. Head and spinal injuries are significantly less common (8-17% and 12.5% respectively). Rock fall accounts for only a small proportion of injuries. (Lack et al., 2012, Paige et al., 1988)

## **Design Communication**

There are two design concepts which have been identified in this investigation, the first being the adoption and popularisation of standardised bolting protocols. The salient features of these system protocols would be:

- An algorithm/ flow chart which makes decision making about the distance between bolts easier
- An increased awareness of the key rock features, such as ledges and cracks, which pose unique risks, and standard methods of bolting to mitigate these risks
- A matrix which compares the probability of a fall and the potential outcomes of a fall in order to assess risk. Probability of fall would be based on the relative difficulty of the section to the remainder of the climb.
- Methods of determining bolt safety and the implementation of standard methods of communicating if a route is unsafe to climb.

These protocols are best communicated by making them freely available amongst climbing communities, publicising them through climbing videos, social media and climbing magazines. A survey of climbers from the ANUMC identified these avenues as key to communication between climbing communities. (Lengyel et al. 2014)

The second design concept is a modification to existing bouldering mats to better meet customer requirements. Bouldering mats are typically not used by sports climbers due to their difficulty of transportation and high cost (Lengyel et al. 2014). One could be incorporating the transportation of other equipment into the mat design which would increase transportability by reducing the number of bags required for gear transport. Another modification would be inflatable bouldering mats. Low cost, low size inflatable bouldering mats do not yet exist. Larger inflatable bouldering mats exist but many require foot pumps, making their portability nullified. The design suggestion would be to design a small scale inflatable bouldering mat that could be inflated by mouth. These designs would be best communicated by CAD modelling, followed by prototyping and adoption by popular athletes in the sport for publicising.

## 1.0 System scoping

Establishing system boundaries involves definition what will and will not be considered in a system of interest. This involves first establishing the use case. The use case is the specific situation which will be considered. Lead climbing, as outlined in the Background section will be the use case. The primary actors are one a lead climber, and one a belayer. The main success scenario is safely completing a conventional “sport climb” of low to moderate height (<30m). This includes potential falls at a variety of heights, and of any length less than that of the entire climb (Cockburn, A, 2001). Specifically, all of the roping, protection, personal equipment and interactions which are involved in the system that facilitates lead climbing will be considered.

Stakeholders in the project will mainly be the climbers themselves. The emergency rescue services, climbing equipment companies and hospitals are secondary stakeholders.

The system boundary chart as seen in table 1. The “Inside” column establishes what will be considered to be part of the system, factors that can be controlled and will be considered important. The “Outside” column lists factors which will be considered as important, but cannot be changed. These factors may affect the system in a manner of ways and these effects are of most interest. The “Excluded” column lists factors which will not be considered. Although they may affect the system as a whole, they will not be taken into account by any system that is derived or in any system analysis. Quality of bolting exists between inside and outside, as it is difficult to change, but could still be considered as a design parameter.

**Table 1 System Boundary Chart**

<b>Inside</b>	<b>Outside</b>	<b>Excluded</b>
Size	Length of Fall	Weather
Weight	Height of fall	Loose rock/ rock fall
Ease of use	Negligence/ distraction	Abseiling
Appearance	Rock surface and morphology	Wet rock
Portability	Difficulty of climb	
Cost		
Ground falls (unprotected)		
Roped Falls		

## 2.0 Requirements engineering

Requirements engineering is the process of understanding, processing and analysing the requirements for a system. This involves going from the customer requirements, which are often vague, under-defined and easily misinterpreted, to well defined technical performance measures. This process may be iterated many times, where customers are consulted several times, in order to produce a clear representation of the customer’s desires. Furthermore, this process is crucial to meaningful evaluation in the late stages of the project. (Hauser, Clausing, 1988)

### 2.1 Pairwise Analysis

Pairwise analysis is a simple method of establishing the relative importance of customer requirements. For this project, a survey of climbers from the Australian National University Mountaineering Club (ANUMC), was used to establish customer requirements. (Lengyel et al. 2014)

Pairwise analysis simply involves comparing customer requirements directly against one another. This is included in ANNEX B. The importance of the design requirements is recorded in figure 2.

## 2.2 Design Requirements and Technical Performance Measures

Design requirements are a refinement on customer requirements. This is the first step in clarifying the problem. Normally, they are simply a more direct, formal or informative wording for the customer requirement. For example, “Easy to use” becomes the more measurable “Ease of use”.

Clear design requirements enable the next step; establishing Technical Performance Measures (TPMs). TPMs are metrics which can be used to measure how well a particular design requirement has been met. TPMs must be clear, based in engineering terminology and must be measurable by an assigned metric. This can be seen in table included in ANNEX C.

## 2.3 House of Quality

The House of Quality (HOQ) is a diagram which summarises the relationships between technical performance measures and design requirements. A HOQ for this project can be found in figure 2. The “Ground Floor” of the house of quality indicates how design requirements and their technical performance measures interact. A symbol indicates how strong the relationship is between the technical performance measure and the design requirement. The technical performance measures are given symbols indicating whether it is desirable to improve, reduce or optimise (target) the technical performance measure. (Hauser, Clausing, 1988)

The “Roof” of the HOQ indicates the relationships between specific TPMs. A positive relationship shows that each TPM reinforces the other. A negative relationship shows that the TPM’s “trade-off”, that is one must be chosen over the other as they have a negative correlation. For example, increasing the yield strength of a material may also increase its ability to take shock loading (in most cases), so there is no trade-off. However, increasing yield strength may involve increasing cost, as stronger materials are often more costly, indicating a trade-off.

### *Key Design Outcomes*

- There are key trade-offs between ease of use and safety. It should be noted that improving the ease of use of a device will increase its likelihood of adoption and therefore, overall increase safety. This is therefore a delicate balance.
- There are key trade-offs between safety and cost. According to the pairwise, safety is more important.
- The system needs to be rethought, and thinking may need to be unconventional. Improving components may simply play into these trade-offs
- The trade-offs could be considered fundamental flaws in the existing system, that may be solved via new subsystems or subsystem interactions.
- TPMs which relate strongly to ease of use do not relate strongly to safety or durability, which indicates a key design consideration which must be taken into account. Again, climbers are prone to be unsafe if equipment is difficult to use, but achieving both design requirements may be difficult.
- Hence there is no one TPM that can be targeted to meet customer requirements.

Correlations	
Positive	+
Negative	-
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

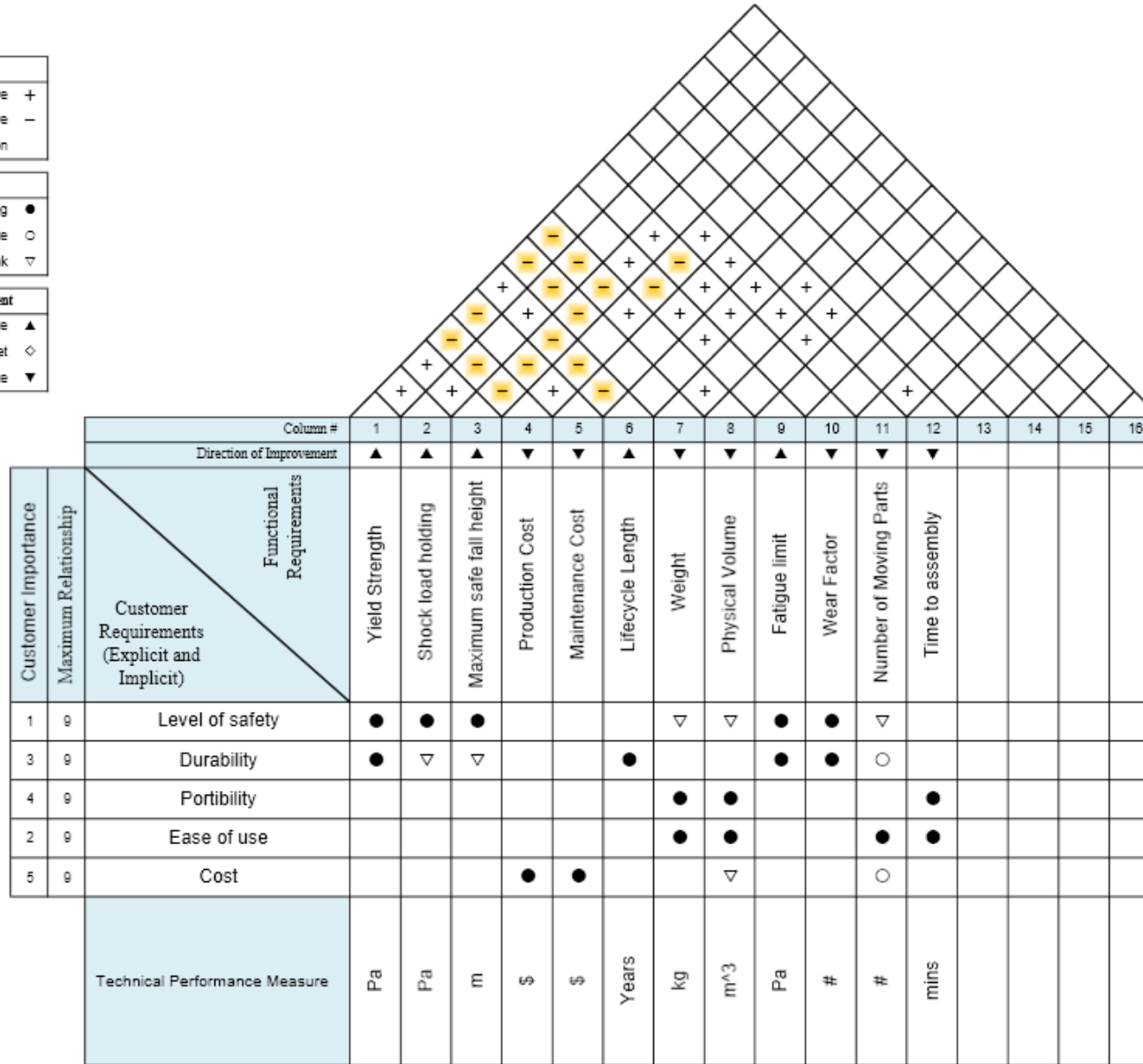


Figure 2 House of Quality

### 3.0 System Function Definition

Functional analysis is the examination of the design requirements and the individual functions of a system. This is done in order to generate concepts and analyse potential systems. There are two methods of doing this, being concept generation and functional flow block diagrams (FFBD). Concept generation and FFBD’s facilitate a systems engineering approach by taking a top-level look at functionality for the overall system. For this project, system functional analysis was completed in order to gain an appreciation of the process involved in lead climbing. This allowed for concept generation by identifying potential areas of danger and areas for improvement in the system which is used.

### 3.1 Concept Generation and Classification

Concept Generation is an efficient and structured method of brainstorming. Ideal brainstorming involves a free flow of ideas, where analysis and judgement are reserved for a later time. Similar concepts are then grouped, and a classification tree is built. This allows for thematic joining of concepts across the different functions of a system or design requirements. Concepts to be continued are highlighted in this tree (Steven, 2013). Concept generation was completed for the project. These concepts were then classified and placed into the classification tree which can be seen in figure 2. (Ulrich, Eppinger, 1995)

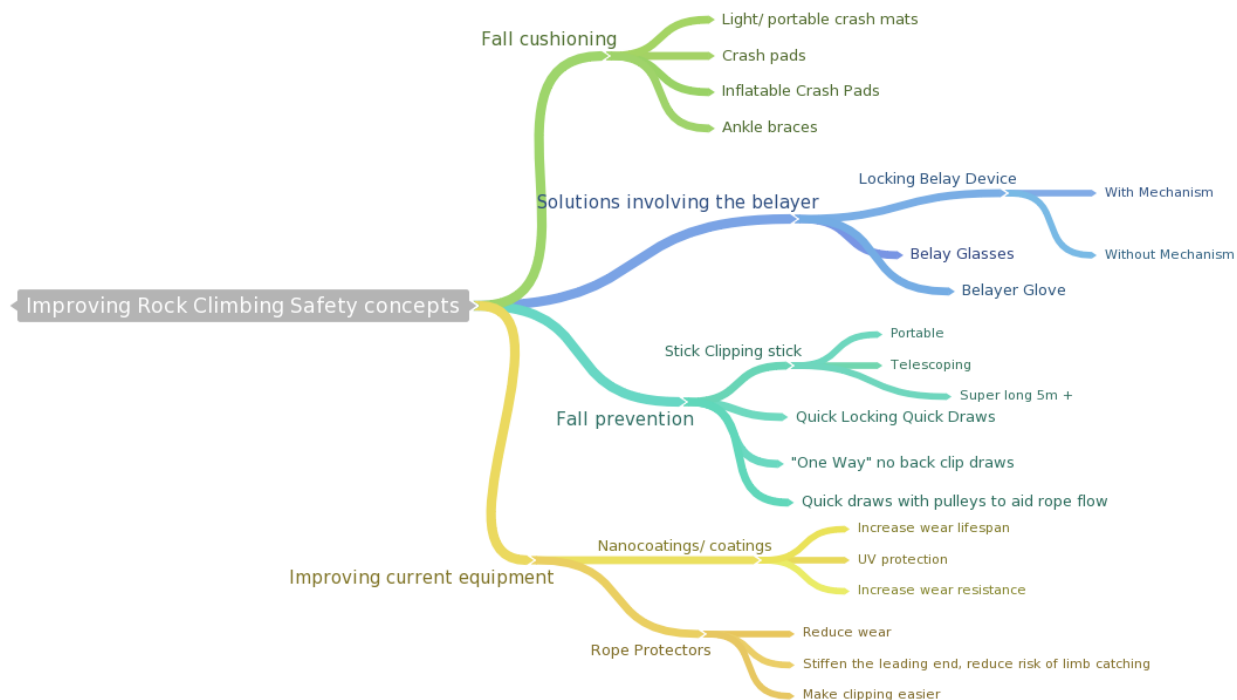


Figure 3 Concept Classification diagram

#### Key Design Outcomes

As can be ascertained from the classification tree that the concepts attempted to meet specific requirements of the system which would improve safety, such as preventing falls, cushioning falls, improving conditions for the belayer and simply improving existing equipment. The classification tree gives a good indication of potential subsystems that could be considered for the design, that is, subsystems dedicated to sets of equipment and their interrelations. For example, solutions involving the belayer could be incorporated into a subsystem, or alternatively, form part of the interactions of the “belayer” subsystem, and other Subsystems.

The classifications attempt to look at the problem holistically, taking a whole-of-system approach to design. There are therefore many avenues for improvement of the system, each with respective difficulties and trade-offs.

### 3.2 Functional Flow Block Diagrams

A Functional Flow Block Diagram (FFBD) is a schematic which outlines the functions and sub-functions of a device. In the top level, tasks to be completed are outlined in a chronological sequence. These top level functions are then decomposed, possibly several times, to make sub-functional blocks. These diagrams can be seen in figure 4 of this report. ‘&’ (and) is used to indicate when *all* steps are required, whereas ‘OR’ is written when *at least one* is required. “Go, no-go” steps (denoted by G and  $\bar{G}$  respectively) indicate where a step may be compromised by machine faults or environmental effects. Maintenance flow block diagrams (MFBD) provide the necessary steps to be completed if the “no go” path is taken. The MFBD may return the user back to the original system after completing some steps, or take the user outside the system for assistance. FFBD’s may be developed for an abstract system, or may consider a single concept or process (Defence Acquisition University Press, 2001.)

The FFBD’s developed for this system can be seen in figure 4. The FFBD will be used in order to ascertain the most likely causes of dangerous falls, and also identify steps in the system that could be altered, or technologies that could be implemented to reduce risk. The FFBD attempts to outline only the most common method of lead climbing.

#### *Key Design Outcomes*

From the FFBD’s we have discovered that in the most part, the actual process of climbing cannot be changed. The process around climbing has existed for many years and this process will not change swiftly.

The FFBD’s have clearly identified many occasions in which falling and ground falls occur. If we focus on the functional steps around these occasions, and derive subsystems or procedures that will mitigate the reason for danger, then the system will be functionally improved. For example, removing the functional step “Climb, place protection” by removing the need to place protection would reduce the risk of falls. This would however imply “Top Roping” or “Bouldering” which are entirely different forms of climbing.

Steps may be implemented to increase safety. The first step would be to include in the set-up a step of setting up a groundfall protection system, such as a bouldering mat. Another step would include a qualitative or quantitative method of determining the quality of bolting before undertaking a route. This could involve checking the bolts before doing the route by abseiling in, although this isn’t always possible, and doesn’t meet the customer requirement of ease of use. A known marker that communicates that a route is unsafe, such as crossed logs at the base of a climb, would potentially improve safety.

The functional step of “Stick Clip First Bolt” is often ignored by climbers, as it can be difficult and dedicated equipment is costly. This means that they must opt for the more dangerous “free climbing” option. Increasing the accessibility and usability of “Stick clipping” devices is one possible solution. Another solution is use of bouldering mats to protect the potential ground fall as noted. Other functional options could be used such as climbing to the first bolt using a ladder, are possible.

The FFBD’s neglect to include transport to the site of climbing, as well as the functional steps which would be undertaken by the belay person, such as setting up the belay device. These were neglected as they are somewhat outside of the use case. These steps may be related back to requirements engineering however, as increasing the portability of the devices will make the transport step easier, and reducing the complexity of the belay device improves ease of use for the belay person.



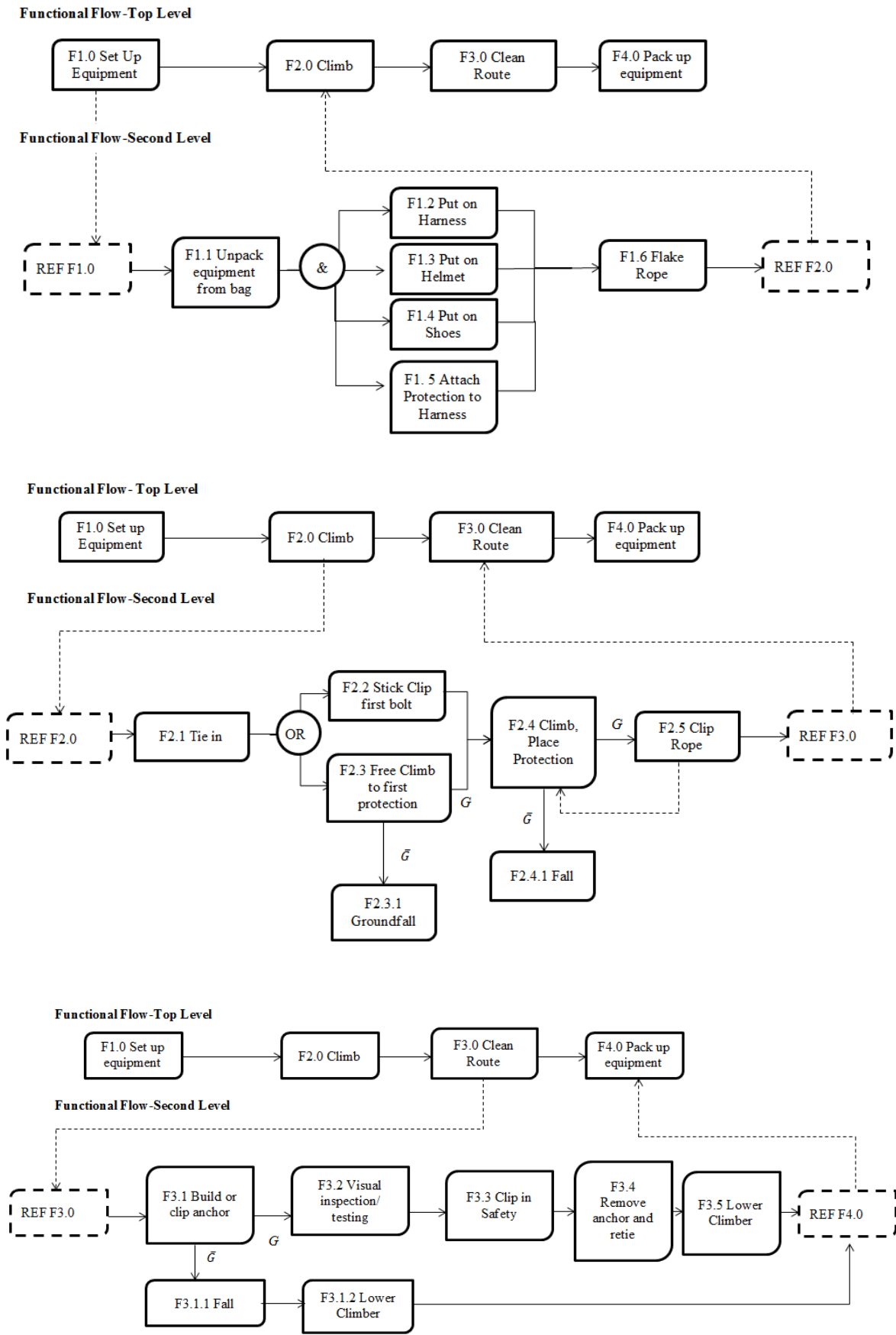


Figure 4 Functional Flow Block Diagrams for lead climbing

## 4.0 Subsystem integration

Subsystem integration is the process on analysing a systems overall inputs and outputs, as well as the subsystems that make up the system. This is done using a Functional Block Diagram. The functional block diagram is helpful in systems design as it allows for a summary of the key interactions and roles of subsystems. This allows for design changes to be imagined in how they will influence the FBD, and how this will affect the outputs of the system. Furthermore, systems can be optimised by streamlining the interactions of systems (Kossiakoff, 2011)

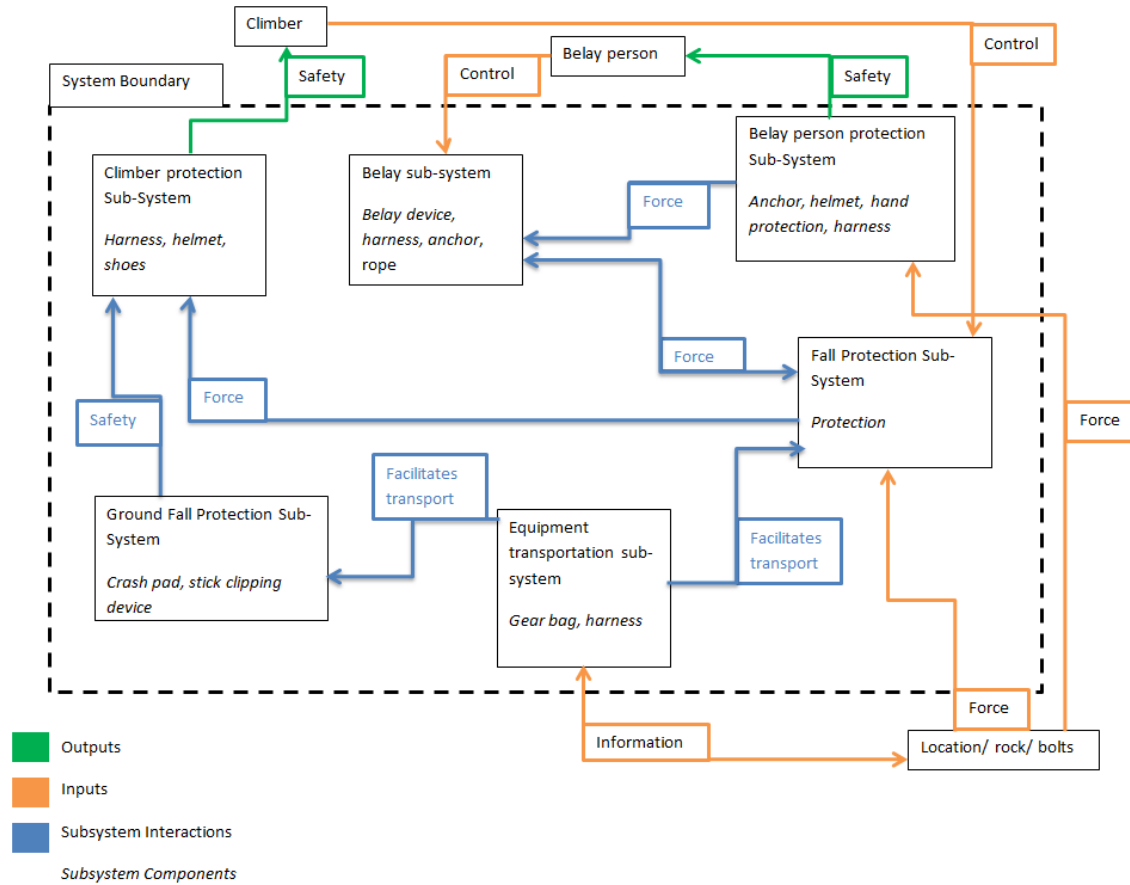
For this project, firstly, the subsystems were scoped. It is important to establish what will be considered a subsystem and what the key inputs and outputs will be, as well as what will be excluded from the FBD. This allows for a smooth development of the FBD. The rock climbing system is broken into five distinct subsystems. The Climber protection subsystem incorporates the personal protective equipment which is used by the climber specifically. Components are seen in the FBD. The Belay-person protection subsystem refers to the equipment which is dedicated to keeping the belay-person safe. This includes an anchor, which is used to prevent injury to the belay-person in case of a fall and other personal protective equipment. It is through these two subsystems that the system interfaces with the climber and the belayer. The Belay subsystem refers to the equipment which is dedicated to controlling the rope, which is the key subsystem which acts as interface between subsystems. The fall protection subsystem refers directly to “protection”. This subsystem has the role of controlling the climber’s fall, as much as possible. The groundfall protection system, is a failsafe to prevent injury on striking the ground, or reducing the probability of groundfall. Finally, the equipment transportation subsystem refers to the equipment dedicated to moving the equipment to and from the climbing site, as well as the harness, which is used to transport protection with the climber to the wall.

In the case of climbing, the main interactions between subsystems are through direct application of force. By definition, all force interactions are opposite and equal. However, the interaction direction implies the more “important” force exchange. That is, the rock provides a force to hold the protection in place, which is necessary for the system to function. The fact that the protection also provides a force to the rock which is equal and opposite is true, however, when visualising the system interactions, this isn’t necessary to be considered as it is more relevant to think of the rock as providing an input or service to the system.

We can also apply “The Five Whys Technique” in analysis of the system to identify key flaws and to get to the root cause of injuries. (Serrat, 2009) For example as seen in the below:

1. The Climber was injured in a fall. Why?
2. Their leg was broken as a result of hitting a ledge (or the ground). Why?
3. The climber struck a ledge (or the ground) with great force. Why?
4. The fall was large in size, the ledge (or ground) was in the falling zone. Why?
5. The climber was a long distance above their protection, the climber was not prevented from contacting the ledge (or ground). Why?
6. Poor bolting procedures

Hence we can see that the root of the problem is rather simple, the climber falls a distance which is too far for the proximity of the surrounding ledges or ground to prevent injury. Hence, a solution may involve implementing procedures which are clear for the bolting of routes.



**Figure 5 Functional Block Diagram**

*Key Design Outcomes*

Most notably we can see from the FBD that the existing system does not include any subsystem for protecting the equipment itself from wear and tear. If detrimental inputs were considered for the system, then it could be considered that the rock inputs wear, abrasion and degradation to equipment. The protection of equipment is normally done at a component level, in the form of coatings and material choices; however, a subsystem could be integrated into the system which would address this issue. This may be a capability of the equipment transportation subsystem, which protects equipment from the elements.

Another point that this FBD raises is the possibility of incorporating or condensing subsystems. For example, could the groundfall protection subsystem be incorporated into the equipment transportation subsystem? This could manifest in the form of a bouldering mat which may be used as a back pack into which other equipment can be packed.

As identified above, bolting procedures may be changed which would influence the interaction of the protection subsystem and the location/ rock. Changing the input of the system may be a powerful method of improving safety, as it would not rely on the equipment itself, thus removing the issues identified in the House of Quality.

It is also noted that the climber and the belayer have responsibilities in controlling subsystems. What if there could be a subsystem dedicated to controlling the interaction of these subsystems? An existing example would be having pre-placed gear, which facilitates movement of the rope and makes climbing easier, and safer. Another option would be automated belay devices, which do not yet exist but could offer fast reaction speeds and would remove human error. Auto-locking devices (which do not require input to hold the rope taught) do exist and remove this interaction.

### 5.0 System Attributes

The attributes cascade relates the customer requirements to the subsystems of the system. This essentially links the entire project and allows for the customer’s requirements to be realised in the final system. This is an integral part of producing a system which meets the customer requirements effectively. In order to do this, the attributes cascade begins with the design requirements, as outlined in section 2. These design requirements are translated into “Primary attributes” which are usually a more descriptive version of the same. The “Secondary Attributes” are then methods of achieving the primary attribute. The “Tertiary Attributes” methods of achieving the secondary attribute. Finally, these tertiary attributes are then linked to the subsystems which are outlined in the FBD. This involves including the subsystems which will be used to achieve the tertiary attributes as well as those that will be affected by achieving that attribute.

The primary attribute of “System Achieves a high level of safety” was chosen as it was identified as the most important customer requirement, and falls directly into the use case. The attributes cascade for “Ease of use” is included in ANNEX D.

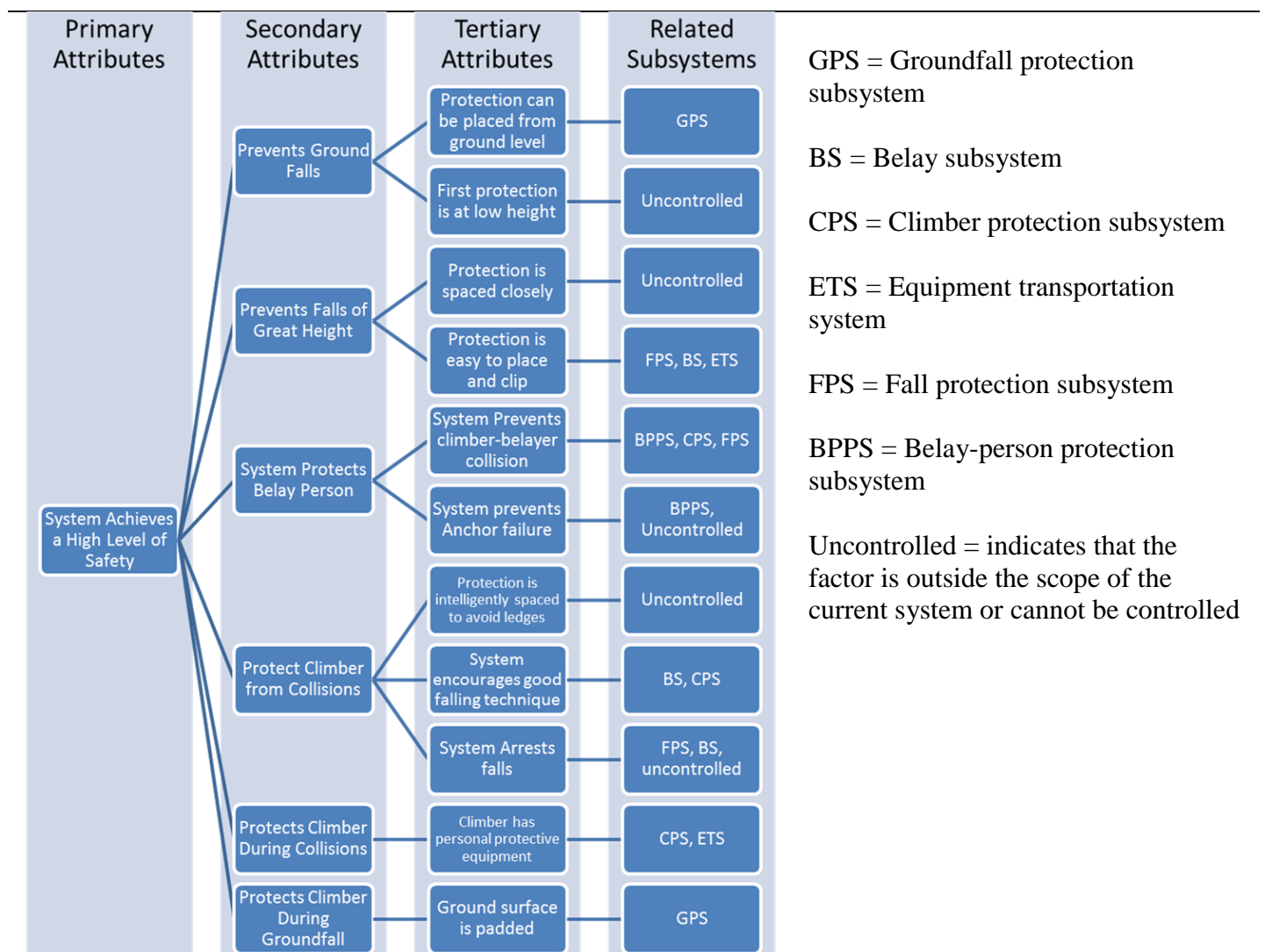


Figure 6 Attribute Cascade for the design requirement “Level of Safety”

*Key Design Outcomes*

The attributes cascade also indicates several major factors about the design. Firstly, we can establish how changes to the subsystems may influence meeting the customer requirements. We can also move the other direction, and observe how changing the importance of primary attributes will filter down to design features which manifest in the subsystems. The attributes cascade also gives clear indication of how subsystems may be closely related, or disparate. This allows for amalgamation of subsystems or further division of subsystem roles. Finally, changes and their “knock on” effects can be better understood

From the attributes cascade, it has become clear that the system does not have subsystems in place in order to achieve some of the tertiary attributes. Introducing protocols, in terms of the bolting of routes would allow for all three of the unknown tertiary attributes to be compensated for. However, this is not necessarily possible, particularly in locations which have already been bolted. Considering bolting is usually done by volunteers, this makes the solution even more complex.

It can also be noted from the attributes cascade that there are several tertiary attributes which are compensated for by equipment that is in existence, but not commonly used. For example, the ground surface being padded is only the case when climbers choose to bring a bouldering mat climbing with them, which is uncommon. Improving the technology of bouldering mats making them easier to use and less costly could better satisfy this tertiary attribute and meet the design requirements. Furthermore, in the groundfall protection system, being able to place protection from the ground is catered for by existing technologies, but they are once again uncommon due to cost and ease of use.

Another point that can be noted is the tertiary attribute that the system itself can encourage good falling technique. This is not a true attribute of the existing system, but could be considered to be an implied attribute that comes from correct training of climbers. An ideal system would implement this attribute via an intrinsic property or mechanical method. Implementing training procedures may be difficult, although publicising falling techniques would be effective, through social media and instructional videos. Interfering with the rope to encourage good falling may be impossible, as it would alter the process of placing protection.

The system attribute of protection being easy to place and clip comes from continual improvements on existing technologies.

The attributes cascade indicates significant relationships between subsystems. For example, the attributes of “System prevents climber-belayer collision” and “Protection is easy to place and clip” are each linked to 3 subsystems. This would indicate two factors. Firstly, a whole-of-system improvement is required in order to meet that tertiary attribute, that is, improving a single subsystem or component will not meet the attribute effectively. Secondly it links back to the trade-offs that were identified in the house of quality (section 2.3). Whatever trade-offs are decided upon must therefore focus on meeting the tertiary attribute. This may require the ascribing of importance to tertiary attributes. For example, “protection is easy to place and clip” is likely less important than “system arrests falls” which would indicate that improving the yield strength and shock load holding ability of protection is more important than reducing the size and weight of devices.

## 6.1 Validation

Design validation is determining that the system design meets the customer requirements by linking the performance of the system back into the engineering requirements derived in section 2 via the tertiary and secondary attributes determined in section 5. (Blanchard, 2006)

**Table 2 Validation Testing**

Tertiary Requirements	Test Type	Procedure	Pass/ Fail Criteria
Protection, intelligent, close spacing and low height	Analytical	A series of protocols could be established for the design of a correctly bolted sports climbing route.	Protocols demonstrate that tertiary attributes are being met.
Ground Surface is padded	Analytical	CAD model or simulation of the set-up of a bouldering mat beneath a climber, with dimensions included, would demonstrate that this attribute is being catered for.	Model demonstrates that the ground surface is in fact padded against a series of simulated falls
Protects climber in ground fall	Proof of Concept	A Technician could then drop a weighted mannequin which has force sensors on critical parts of the body onto the protective device from varying heights, with adequate repetition and determine if the force exerted on the body was sufficient to cause damage. A further test could involve placing the device on many variable surfaces.	The mannequin could have a survivable fall from a height of 5m as determined by force gauges
Protection, intelligent, close spacing and low height	System Prototype	This could involve having an indoor climbing gym set up which is analogous to the outdoor situation. This would have the facility to change protection locations and implement concepts and test results	The climber can fall at any point in the indoor system without risk of injury

### *Key Design Outcomes*

Many of the secondary attributes are quite qualitative, and would only become evident in being met, after much testing and even survey over many years, to indicate that the attribute is met. The concepts developed would be very likely to meet these verification tests.

## 6.2 Evaluation

An Evaluation matrix is found in table 3. (Hauser, Clausing, 1988).

**Table 3 Evaluation Matrix**

Customer Requirement	Rank	Weighting	Improved Groundfall Protection mat		Improved Bolting Protocols		Improved Belay Devices		Improved Quick draws		
			Compliance	Weighted Value	Compliance	Weighted Value	Compliance	Weighted Value	Comp	Weighted Value	
Safe	1	5	4	20	5	25	1	5	1	5	
Durable	2	4	3	12	3	12	5	20	3	12	
Low Cost	5	2	3	6	1	2	5	10	3	6	
Highly Portable	4	3	1	3	5	15	4	12	5	15	
Easy to use	2	4	5	20	5	20	3	12	5	20	
				61			74			59	58

Durability was based on how often the devices need replacing, which is common knowledge to many climbers. Bouldering mats, bolts and quick draws can need replacement every 3 years, whereas belay devices can last significantly longer if not misused. Cost is based off values determined from an online supplier, (climbinganchors.com) and ease of use is based upon personal experience.

### *Key Design Outcomes*

Clearly, the design evaluation has shown that improving bolting protocols is evaluated to be the best solution. If we perform a sensitivity analysis, it is clear that this is a result of the associated ease of use and high portability. Improved bolting protocols would be incredibly easy to use and highly portable (the bolts are permanently in the wall) following an initial period of high upfront cost and large time investment. Thus, this solution may be better suited to situations where re-bolting is already to be implemented. Bolting is often done at the expense of an individual however, and other climbers often don't bear the cost. Hence, from the perspective of a climber who has not done bolting themselves, this could be an ideal solution.

Importantly it can be noted that the bouldering mat is limited by the fact that it is not highly portable, and its associated cost is rather high. This me would imply that increasing the portability and reducing the cost of bouldering mats, perhaps by an inflatable alternative, then this would make them a desirable solution. The aforementioned incorporating of the bouldering mat into gear transportation is also an option. A limitation of the evaluation matrix may be that it cannot fully evaluate the incorporation of subsystems as seen in this solution.

Improved Belay devices offer a high-scoring alternative but this avenue has been explored extensively in the field to little improvement on safety.

## References

- Blanchard, Benjamin S., and W. J. Fabrycky. 2006 Systems Engineering and Analysis. Upper Saddle River, NJ: Pearson Prentice Hall,. Print.
- Cockburn, Alistair. 2001 "Introduction to Use Cases." Writing Effective Use Cases. Boston: Addison-Wesley,. 16-26. Print.
- Defence Acquisition University Press 2001. Funticonal Analysis and Allocation. In: Defence Acquisition University Press (ed.) Systems Engineering Fundamentals. Virginia, USA: Defence Aquisition University Press.
- Hauser, John R., and Don Clausing. 1988The House of Quality. Boston, MA: Harvard Business School, Pub. Division,. Print.
- Kossiakoff, Alexander. 2011 "Functional Analysis and Design." Systems Engineering: Principles and Practice. Hoboken, NJ: Wiley-Interscience,. Print.
- Lack, D. A., Sheets, A. L., Entin, J. M. & Christenson, D. C. 2012. Rock Climbing Rescues: Causes, Injuries, and Trends in Boulder County, Colorado. Wilderness & Environmental Medicine, 23, 223-230.
- Lengyel, Phil, Warren Price, Chris Elliot, and Kate Ferguson. "Addressing Safety Issues in Rock Climbing." Online interview.
- Paige, T, E., Fiore, D. C. & Houston, J. D. 1998. Injury in traditional and sport rock climbing. Wilderness & Environmental Medicine, 9, 2-7.
- Ropebook. 2012. Fall Factors [Online]. Rope Book.
- Serrat, Oliver, and Stephen Banta 2009.. "The Five Ways Technique." Independent Evaluation at the Asian Development Bank. Manila , Philippines: Operations Evaluation Department, Asian Development Bank, Print.
- Steven, S. 2013. Concept Generation and Functional Decomposition.
- Ulrich, Karl T., and Steven D. Eppinger 1995. "Concept Generation." Product Design and Development. New York: McGraw-Hill,. Print.