MASTER

Design and engineering of a mobile intensive care unit for pediatric interhospital transport

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Design and engineering of a Mobile Intensive Care Unit for pediatric interhospital transport

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# Contents

Summary .......................................................... vii

1 Introduction ................................................. 1
   1.1 Introduction ........................................... 1
   1.2 Definitions ............................................ 2

2 Demands and design principles for the MICU ......... 3
   2.1 Transport procedure .................................... 3
   2.2 Design principles for the MICU ....................... 3

3 Wheels under the MICU .................................... 5
   3.1 Options for wheels under the MICU .................. 5
   3.2 A combination of rigid and swiveling castor ....... 6
   3.3 Mounting the wheels on the undercarriage ........... 7
   3.4 Operation of the locking mechanism of the wheels . 8

4 Mechanism ................................................... 11
   4.1 Concepts for the mechanism ......................... 12
   4.2 Design of a four bar mechanism ..................... 13
   4.3 Main dimensions and loads on the mechanism ....... 14
   4.4 Design of the mechanism ............................. 17
      4.4.1 Bearings ........................................... 18
      4.4.2 Axle s in beam 1 ................................ 19
      4.4.3 Axle q in beam 1 ................................ 21
      4.4.4 Beam 1 ............................................ 22
      4.4.5 Axle r in trendelenburg bar .................... 24
      4.4.6 Beam 2 ............................................ 25
   4.5 Drive of mechanism .................................... 26
      4.5.1 Parallelogram for displacement of trendelenburg actuator ........................................ 26
      4.5.2 Actuator choice ................................... 26
      4.5.3 Pump ............................................. 28
   4.6 Stiffness of the mechanism ........................... 28
   4.7 Fixation of mechanism ................................ 31
   4.8 Final design ............................................ 32

5 Bed ............................................................. 35
   5.1 Fixation of patient ................................... 36
   5.2 Fixing the matras on the bed ......................... 37
   5.3 Fixation of the bed on the connection plate ....... 38
      5.3.1 Making space under the bed for making x-rays ........................................ 38
      5.3.2 Options for fixation of the bed on the connection plate ................................... 39
   5.4 Final design ............................................. 40
6 **Lay-out of apparatus** 43
   6.1 Principles for placement of apparatus 43
   6.2 Apparatus to be used in the MICU 44
      6.2.1 Overview 44
      6.2.2 Gas cylinders 44
      6.2.3 Batteries 46
      6.2.4 Ventilation 46
      6.2.5 Perfusion pump 48
      6.2.6 Suction unit 49
      6.2.7 Monitor 50
      6.2.8 Module rack 51
      6.2.9 Defibrillator 52
      6.2.10 Medication and disposables 52
   6.3 Final lay-out 53

7 **Fixation of the MICU in the ambulance** 55
   7.1 Forces acting on the MICU 55
   7.2 Energy absorption in plastic deformation 56
   7.3 Testing of energy absorption strips 59
   7.4 Fixation of the MICU 61
      7.4.1 Connection of the MICU to the energy absorbing fixtures 61
      7.4.2 Energy absorbing fixtures 66

8 **The undercarriage of the MICU** 69
   8.1 Mounting of mechanism and hydraulic cylinders 70
   8.2 Lay-out of compartment 1 71
   8.3 Optimization of undercarriage using FE element simulations 72

9 **Loading the MICU in the ambulance** 83
   9.1 Tailboard 83
   9.2 Loading the MICU without a tailboard 84

10 **Conclusions and recommendations** 85
    10.1 Conclusions 85
    10.2 Recommendations 86

**Bibliography** 87

A **Wheels** 89
   A.1 A combination of rigid and swiveling castor 89
   A.2 Information on Colson Medical Castors 90

B **List of equipment** 91

C **Drive of scissor lift** 93

D **Calculation of forces on the mechanism** 95

E **Dimensioning of axles** 101
   E.1 Dimensioning of axle q in beam 1 101
   E.2 Dimensioning of axle r in trendelenburg bar 102

F **DU-B bearings** 103
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>Energy absorption in bending of a strip</td>
<td>107</td>
</tr>
<tr>
<td>G.1</td>
<td>Tensile test</td>
<td>109</td>
</tr>
<tr>
<td>G.1.1</td>
<td>Testing of energy absorption strips</td>
<td>111</td>
</tr>
<tr>
<td>H</td>
<td>Concepts for loading of MICU into the ambulance</td>
<td>113</td>
</tr>
<tr>
<td>H.1</td>
<td>Basic concepts</td>
<td>113</td>
</tr>
<tr>
<td>H.2</td>
<td>Concept (a): Equipment under the bed</td>
<td>114</td>
</tr>
<tr>
<td>H.3</td>
<td>Concept (b): Equipment on the ground</td>
<td>114</td>
</tr>
<tr>
<td>H.3.1</td>
<td>Concept (b1): Lifting upright</td>
<td>115</td>
</tr>
<tr>
<td>H.3.2</td>
<td>Concept (b2): Undercarriage inclined, bed lifted upright</td>
<td>116</td>
</tr>
<tr>
<td>H.4</td>
<td>Concept (c): Equipment can be lifted to the bed to drive into the ambulance</td>
<td>117</td>
</tr>
<tr>
<td>I</td>
<td>Construction drawings</td>
<td>119</td>
</tr>
<tr>
<td>J</td>
<td>Plate thickness of undercarriage</td>
<td>125</td>
</tr>
<tr>
<td>K</td>
<td>List of symbols</td>
<td>127</td>
</tr>
<tr>
<td>Samenvatting</td>
<td>129</td>
<td></td>
</tr>
<tr>
<td>Dankwoord</td>
<td>131</td>
<td></td>
</tr>
</tbody>
</table>
Summary

Recent developments in providing intensive care for children favor centralization of care in tertiary centers [1]. Critically ill children show a better clinical outcome when treated in tertiary pediatric intensive care units than when treated in other pediatric centers. Centralization of intensive care requires transport from the referring hospital to the tertiary facility centers. Specialized pediatric retrieval teams must provide all equipment and materials necessary for advanced life support and emergency treatment of children of all ages and body weights in order to bring the level of therapy and monitoring during the period of stabilization and transport as close as possible to that of pediatric intensive care units (PICU).

A transport unit based on a standard ambulance trolley has been developed in the university hospital of Maastricht (AZM). Making use of such a unit to transport equipment, medication and the patient is proven to be successful, but safety and stability of this unit are insufficient.

Problem statement:

Design a mobile intensive care unit (MICU) that enables the transport team to transport equipment, medication and the patient in a safe and easy way.

Therefore the demands to such a unit are investigated and design principles are stated. In discussion with the 8 tertiary centers in the Netherlands, the lay-out of the equipment on the MICU is determined. All equipment is stored in the undercarriage. The lay-out of the equipment provides a good sight on the equipment and enables the transport team to reach all equipment, but also provides an optimized concentration of mass and a low center of gravity. The wheels on the MICU provide good driving properties and enables the transport team to park the MICU besides the bed of the patient in the referring hospital. Because all equipment is stored in the undercarriage, no equipment is stored on the bed and the patient can be reached from all sides. A mechanism is designed to lift the bed from ambulance position to working position, but also provides trendelenburg and anti-trendelenburg positions. Furthermore, the mechanism is crashworthy. The bed can be taken apart from the mechanism. And because the bed is fully made of epoxy fiber composite, x-rays can be taken without lifting off the patient. The patient can be crashworthy fixated on the bed. The fixation of the MICU in the ambulance provides energy absorption in a crash. When a 20 g crash occurs, an extra brake path of 100 mm is provided where the energy is absorbed in deformation of the energy absorbers. The construction of the undercarriage is optimized for a 20 g crash.

A safe and easy to use mobile intensive care unit has been designed. A prototype of the MICU will be build by the GTD at the TU/e. Further development will be done in conversation with the tertiary centers.
Chapter 1

Introduction

1.1 Introduction

Recent developments in providing intensive care for children favor centralization of care in tertiary centers [1]. Critically ill children show a better clinical outcome when treated in tertiary pediatric intensive care units than when treated in other pediatric centers. Centralization of intensive care requires transport from the referring hospital to the tertiary facility center (see figure 1.1).

From literature is known that interhospital transport of critically ill children by non-trained personnel tends to be associated with a higher incidence of major complications than transport by specialized pediatric retrieval teams. Specialized transport teams are able to produce a high degree of stabilization of the patient prior to and during transport. Specialized pediatric retrieval teams must provide all equipment and materials necessary for advanced life support and emergency treatment of children of all ages and body weights in order to bring the level of therapy and monitoring during the period of stabilization and transport as close as possible to that of pediatric intensive care units (PICU).

A transport unit based on a standard ambulance trolley has been developed in the university hospital of Maastricht (AZM). Making use of such a unit to transport equipment, medication and the patient is proven to be successful, but safety and stability of this unit are insufficient.

Problem statement:

Design a mobile intensive care unit (MICU) which enables the transport team to transport equipment, medication and the patient in a safe and easy way.

Therefore the demands to such a unit are investigated and design principles are stated in chapter 2. These principles are used to design the wheels (chapter 3) and the mechanism to lift and rotate...
the bed (chapter 4). The design of the bed and the fixation of the patient is explained in chapter 5. The placement of the equipment is subject of chapter 6. The fixation of the MICU is explained in chapter 7, the design and dimensioning of the undercarriage on basis of finite element simulations of a 20 g crash is subject of chapter 8. Loading the MICU in the ambulance is subject of chapter 9. Conclusions and recommendations can be found in chapter 10.

1.2 Definitions

In figure 1.2, the names of the parts of the MICU are explained. The bed can be lifted and rotated on a mechanism between the bed and the undercarriage that contains the equipment. The connection plate is used to connect the bed to the mechanism. The console can be used to push the MICU and to operate the mechanism.

![Diagram of MICU parts and axes definition](image.png)

Figure 1.2 - Names of the parts of the MICU and definition of axes

The length axis of the MICU is defined as the x-axis. The positive x-direction corresponds with the driving direction of the ambulance when the MICU is loaded in the ambulance. The z-direction is the vertical axis.
Chapter 2

Demands and design principles for the MICU

In order to understand what is important for the MICU, the operating procedure of the transport team is explained in section 2.1. The demands on the MICU are combined with technical principles. Design principles for the MICU are presented in section 2.2.

2.1 Transport procedure

When transport is needed for a patient from the referring hospital to the PICU (pediatric intensive care unit) of the university hospital, an appointment for transport will be made. The transport is normally arranged for within a few hours, high speed emergency transports are rarely performed. The transport team consists of a pediatric intensivist, a nurse from the pediatric intensive care, a paramedic of the ambulance and a driver. The last actions are taken to prepare the MICU for transport and then it is loaded in the ambulance. The ambulance transports the MICU to the referring hospital. The MICU is driven to the department of the patient to be transported. The personnel parks the MICU besides the bed and lifts over the patient to the bed on the MICU. The patient will now be stabilized by the transport team before the transport from the referring hospital to the receiving tertiary facility center will take place. They can make use of the gas and electrical circuit of the hospital in order to save oxygen, air and batteries for transport. When the patient is stable, the transport back to the tertiary facility center will be prepared. The patient is fixed on the bed. Gas and electrical connections are switched to the gas cylinders and batteries. And the MICU is driven to the ambulance. The MICU will be loaded in the ambulance and fixated. The unit is connected to the gas and electrical supplies of the ambulance. During transport, the pediatric intensivist sits on a chair at the head end of the MICU and the nurse is sitting next to the patient. They will keep an eye on all vital signs of the patient and the function of the equipment. Medical interventions are performed if necessary. When the transport team arrives at the university hospital with their patient, the MICU will be unloaded from the ambulance and transferred into the intensive care unit. If necessary, first further investigations, like x-ray, are performed on the emergency department.

2.2 Design principles for the MICU

The demands on the MICU are combined with technical principles. This results in the design principles as presented in this section.

**Undercarriage contains all equipment** All equipment is stored in the undercarriage. The placement of the apparatus is optimized for use during transport, concentration of mass
and a low center of gravity. The last 2 items are essential for stability and crashworthiness. Furthermore, the bed is now free from equipment, so the patient can be approached from all sides, which is desired for lifting the patient from the hospital bed to the MICU and for stabilization.

**Equipment visible from sight angle** Because good sight on the equipment is necessary during transport, the equipment is placed under an angle to make it visible and reachable for the transport team. This angle can be determined. (see figure 2.2). Based on the height of a seat for the average man (455 mm) and a woman (407 mm) and the height of the eye for an average man (814 mm) and an average woman (757 mm), a height of the eye with respect to the ambulance floor of 1220 mm is assumed. Based on the buttock-knee-depth of 617 mm for an average man and 605 mm for an average woman and assumptions for the distance between the back of the head and the eye (160 mm) and for the distance between the chair and the MICU (200 mm), a distance of 650 mm between the eye and the front wall of the MICU is assumed.

![Figure 2.1 - Sight angle](image)

**Every mass makes its own collision** All apparatus are fixed in their own compartment of the undercarriage and the patient is fixed on the bed in such a way that energy can be absorbed in case of a collision.

**Absorption of energy in case of collision** A rigid fixation transmits the forces directly to the MICU and the patient. When a part of the kinetic energy is absorbed for example between the MICU and the ambulance, forces on the MICU are reduced. When energy is absorbed during travel s of the mass, the absorbed kinetic energy equals the work W of the force F on this mass: \( W = F \cdot s \). It is easy to see that energy absorption over a longer travel s results in a relatively lower force F.

**Bed is suitable for x-ray and CT scan** The bed can be made from epoxy fiber composite and foam. This material allows x-ray to pass. Therefore, the bed does not contain steel parts unless the steel parts are fully enwrapped and placed outside the area where x-rays must be made. The bed can be lifted off the mechanism in order to transport the patient to the CT-scan without lifting over the patient. The tubes and cables connected to the patient must be long enough. They are fixed to the bed to prevent pulling the patient. X-rays of the patient lying on the MICU could be made when there is enough space under the bed for the x-ray unit.

**Wheels of the MICU** The wheels enable smooth transport. The MICU is manoeuvrable and rolling away must be prevented.

**Mechanism for the bed** Because treatment of the patient can be done in the hospital or in the ambulance, the bed can be lifted from transport position (horizontal position at 700 mm above the floor) to working position (about 1250 mm from the floor). Rotation of the bed around the y-axle is needed for trendelenburg and anti-trendelenburg positions (30°).
Chapter 3

Wheels under the MICU

Because the MICU is meant to transport a patient from a department in the referring hospital to the (pediatric) intensive care unit of the tertiary facility center, the MICU must be able to travel over linoleum floors in the hospital, concrete floors and bricks outside the hospital (which is only a small distance, because the ambulance is parked in an ambulance garage or near the doors) and into the ambulance. Therefore, wheels are mounted under the MICU. The wheels enable smooth and stable transport with maximum comfort for the patient and the transport team. Steering has to be easy and effective and rolling away must prevented.

3.1 Options for wheels under the MICU

(a): In figure 3.1 several options for wheels under the MICU can be seen. Option (a) presents four castor wheels, which make the MICU manoeuvrable. Parking the MICU beside the bed of the patient is easy with four castors, but driving a straight way through the passageway of the hospital is difficult.

(b): In order to enable this, two normal wheels and two castor wheels are a better option (see figure 3.1(b)).

(c): Another option is four wheel steering (see figure 3.1(c)). The movements of the back and front wheels are coupled. A smaller turning circle can be made with this option, but the parking problem is still present.

(d): A fourth option is a so called diamond lay-out where one axle is rigid and one castor is at the front and one at the back. Large wheels can be mounted on the rigid axle. The two castors at
the front and the back are mounted on a weak spring, so they will always stay in contact with the floor. Another advantage of this option is that it could rest with three wheels on a short tailboard, when this is applied on the ambulance. A disadvantage of this option is the instability. A force outside the rhombus between the wheels could result in turning over of the MICU.

(e): Stability is increased when two castors are mounted at the front and 2 castors at the back (see figure 3.1(e)). This will cost two extra wheels and the space in the undercarriage to mount them.

(f): The last option presents caterpillar tracks. This could be an optional feature. The tracks could be folded out of the box and drive the MICU outside the dirt, when an accident with the ambulance has occurred, or when this MICU is made suitable for all other transports than interhospital transport. The tracks could be folded in a box in the undercarriage before entering the ambulance or hospital and keep the dirt in the box.

A combination of options (a) and (b) is needed to enable the MICU to be driven straight on and also manoeuvred in every corner with four castors. In the next paragraph, we will take a look at possible combinations of option (a) and (b).

3.2 A combination of rigid and swivel castor

An optimal combination of the options (a) and (b) are four castors under the MICU. The demands for such castors are:

- The swiveling of the wheel can be locked.
- The swiveling of the wheel can only be locked in driving straight forward or backward position.
- Driving must be possible when swiveling of the wheel is locked.

Locking the swiveling of castors can be done in a few ways. These options are presented in appendix A. The options presented will be special-made products in a workshop. Therefore the wheels become very expensive and back up wheels cannot just be ordered from the catalogue, but have to be special made. Therefore commercially available wheels are preferred.

Medical castors (see figure 3.2(a)) can be delivered with a total and directional locking mechanism [2]. The cam in the vertical axle of the wheel can be rotated in three positions: free position, directional lock and total lock. The directional locking position allows free rotation of the wheel, but when the MICU is driven, it locks the swiveling of the wheel as soon as it is rotated in x-direction. These wheels answer the demands on the castors under the MICU and rolling away of the MICU can be prevented using the total lock position.
Because these castors are especially for hospitals, they are also hygienic and operate smoothly. Due to the relatively small bearings the required space to build in the wheels is relatively small. The load capacity of 150 kg per wheel is less than for industrial castors, but enough for the MICU. The costs of these wheels differ from 60 to 80 euro for medical castors with a 150 mm diameter. Load capacity is larger for bigger wheels. Such large wheels make the MICU roll better and obstacles can be taken better.

The combi wheels with total and directional lock from Colson Castors are used for the MICU. Detailed information can be found in appendix A.

In order to extend the life of the wheels, the MICU could be stored in a docking station or a plunger lock could be applied to unload the wheels when the MICU is not used.

### 3.3 Mounting the wheels on the undercarriage

The track and the height of the center of gravity determine the stability of the MICU. The angle $\alpha$ in figure 3.3 is the stable angle that the MICU may rotate around the line between the front and back wheel (at one side) before it turns over. This angle is constructed by the line through the middle of the wheel and the center of gravity and the vertical line through the middle of the wheel. A wide track and a low center of gravity result in a stable construction.
The mount of the wheel is sectioned in x-direction and in y-direction of the MICU in respectively the left and the right part of figure 3.4(a).

![Figure 3.4 - Mounting of wheels to the undercarriage](image)

The wheels must be mounted as far apart as possible and may not be in the way for the nurse or doctor walking behind the MICU. The center of the axle is mounted 25 mm apart from the side wall of the MICU (C), so a track width of 600 mm can be realized. The wheels can swivel one half round in the wheel houses, but when swiveling outwards, the wheels stick out of the wheel house. This compromise is made to keep the track width as wide as possible and to have as much space as possible between the wheel houses.

The vertical axle of the wheel is inserted in a bush (B). This bush is fixed between the wheel house (A) and an extra plate (D). The bush is welded to both plates. Therefore, the radius of the bush is reduced with one millimeter on two sides over a length of the plate thickness in order to fix the bush into the plates. The edge is chamfered to make a solid K-weld.

A plate is bent 90 degrees to form part D of the mount. Rectangular holes with a width equal to the wall thickness of the wall (C) are cut from it (see figure 3.4(b)). Corresponding holes are made in the wall. This makes a stiff and strong closed box where welding is only needed to hold the plates in their position and transmission of forces occurs on shear of the merlons. The surface of the wall and the upper plate of the wheel house is not very smooth due to this way of fixating, but in the wheel house, this cannot be seen. The welds on the side wall of the MICU are hidden under the bumper.

Holes are made in the sidewalls of the bush for bolts. The holes in the sidewalls F of the box have a diameter of 12 mm. A small bush with an inner diameter of 8 mm (E) is used to space the bolt. This bolt is therefore easy to reach and can now be longer, which results in more strain in the bolt and a more constant force on the wheel.

A ground clearance of 100 mm is sufficient for the MICU. Therefore, the wheel houses are 65 mm high. This construction lowers the center of gravity with the same distance.

### 3.4 Operation of the locking mechanism of the wheels

The locking mechanism of the wheels can operate in three ways: total lock, free position and directional lock. Switching between those positions can be done by rotating a cam shaft in the wheel (see figure 3.2). The two wheels at the front and the two at the back are coupled, because these wheels must always be in the same situation. The wheels are coupled with two cables. A cam (A and B in figure 3.5) is mounted on the cam shaft. A steel cable (C) is fixed on this wheel in such a way that a large surrounded part of the cam is created. The cable leads through a hollow cable (E) to the other cam. The other cable (D) is fixed to the wheel in the same way. This combination of a cable in an outer cable is called a bowden cable. The outer cable provides the pretension on the inner cable. Therefore, the outer cable is mounted to the undercarriage. To provide the adjusted pretension, a spring is mounted between the undercarriage and one of the
3.4. **OPERATION OF THE LOCKING MECHANISM OF THE WHEELS**

outer cables. This pretension will rotate the wheels with respect to each other, which is a point of attention in the assembly.

![Figure 3.5 - Bowdencable](image)

The lever or button to operate the wheels is made in the console. Rotating the cam shaft in order to operate the wheels requires a maximum moment of about 4 $Nm$. This moment was determined experimentally by pulling a spanner with a steelyard.

When a construction with bowden cables is used, a cam is mounted on the cam shaft of the wheels. The radius of the cam can be maximal 30 mm. A larger cam would cut the plate in which the wheel in is mounted (D in figure 3.4(a)). When this moment is applied directly, an operating force of $F = \frac{M}{r} = \frac{4 \times Nm}{30 \times mm} = 135 N$ is needed. A transmission is desired to operate the locking mechanism of the wheels with a smaller force.

A transmission is presented in figure 3.6. A bowden cable is used to couple the wheel on the camshaft (A) to the wheel in the console (B). The operation force $F_3$ and travel $s_3$ on the lever (C) can be determined.

![Figure 3.6 - Transmission for operating of the wheels](image)

The force can be determined as a function of the radii of the wheels 1 and 2 and the length of the lever $l$.

$$F_3 = \frac{M_1 R_2}{l R_1}$$

$$s_3 = \frac{1}{4} \frac{R_3}{R_2} \pi l$$

When $F_3$ is 40 $N$, $l = \frac{M_1 R_2}{R_1} = \frac{4 \times Nm R_2}{R_1}$. When the radius of wheel B equals the radius of wheel A, a lever of 100 $mm$ is needed. The travel $s_3$ is 80 $mm$. 
The mechanism is the connection between the undercarriage and the bed. This mechanism must lift the bed from the ambulance position to working position and rotate it in order to provide trendelenburg and anti-trendelenburg positions. These four different positions are presented in figure 4.1.

Figure 4.1 - (a) Working position (b) Ambulance position (c) Trendelenburg position (d) Anti-trendelenburg position

All other movements of the bed must be prevented. Furthermore, the bed must be fixated crash-worthy. In the ambulance the bed is always in the ambulance position, so extra connections to the undercarriage can be made.

Concepts for the mechanism are the subject of section 4.1. The design of the chosen concept is subject of section 4.2, the main dimensions and loads on the mechanism are determined in section 4.3. The junctions, beams and axles are designed and dimensioned in section 4.4. Drive of the mechanism is the subject of section 4.5. The stiffness is determined in section 4.6, fixation of the mechanism is subject of section ?? and the final design is explained in section 4.8.
4.1 Concepts for the mechanism

Five different concepts for the mechanism are presented in figure 4.2. The bed is marked with A and the undercarriage with B.

(a): One big cylinder (C) can be used between the bed and the undercarriage (see figure 4.2(a)). Operation tables are made like this because of the space under the bed. Mounting the cylinder (C) will cost a lot of space in the middle of the undercarriage. The stiffness of the bed in x and y-direction is low because it is based on bending of the telescope and stiffness of the guiding. The trendelenburg positions cannot be made with this mechanism, so another mechanism to rotate the bed must be applied.

(b): More space under the bed and a stiffer construction can be made when three or four cylinders (D) are used to lift and support the bed, which can be seen in figure 4.2(b). Trendelenburg positions can be reached when the telescopes at the front are on different height as the ones at the back. A large rotation can only be made when the change in distance between the cylinders can be adjusted. Fixation of the bed in x, y and θ is based on the bending stiffness of the cylinders.

(c): The rotation around the z-axis and translation in y-direction of the bed can be defined by two rods in y-direction. These rods could be replaced by a folded leaf spring under the bed. Because of the large stroke, a two-stroke can be used to define the DOFs y and φ (see figure 4.2(c)). A lot of space is present under the bed for the röntgen unit.

(d): A scissor lift (G) is also suitable to lift the bed and define the rotations around all axes relatively stiff. Trendelenburg positions must be reached with another mechanism under the bed. The legs of the scissor do not leave space under the bed for a röntgen unit. A disadvantage of options (a), (b) and (c) is the space required in the undercarriage for mounting of actuators. Drive of this mechanism can be done by an actuator under the bed or on top of the undercarriage. An option for actuation of this mechanism is presented in appendix C.

(e): Figure 4.2(e) represents a bar mechanism. Lifting the bed could be done by an actuator in the undercarriage that rotates one of the bars (like a jack) or with an actuator that pushes up the bed directly. This mechanism only requires space in the undercarriage at the back for turning points and actuation. Stiffness in z-direction is based on stiffness of the actuator and bending of the lifting bar. The other bar defines the rotation of the bed around the y-axis. The mechanism can be seen as a guiding of the bed in the direction between turning points r and s. Because this direction could be changed, this mechanism can also be used to rotate the bed to trendelenburg position. One of the bars (H or I) consists of two bars in order to provide rotational stiffness around the z-direction.
4.2 DESIGN OF A FOUR BAR MECHANISM

Because

- the bars in driving direction provide stiffness from push and pull of the bars in the different positions of the mechanism and in a crash
- drive of the mechanism can be done in one part of the undercarriage
- one mechanism can be used to lift the bed and rotate the bed to the trendelenburg positions
- a lot of space is left between the bars for x-rays

this option is worked out in the next section.

4.2 Design of a four bar mechanism

Because the center of gravity of the patient is on the middle of the bed, beam 1 is always under tension and beam 2 is under pressure. Lifting the bed with one of the beams will result in bending of this beam. Therefore, beam 1 is chosen to lift the bed. The other beam is realized as two beams, which is also the best lay-out in order to keep free sight on the equipment (see figure 4.3). Rotation of beam 1 will result in lifting the bed. The bed is lifted in the direction of the line between points r and s.

![Figure 4.3 - The beams of the mechanism allow sight on equipment](image)

The trendelenburg position can be reached when the beams are both horizontal and the line between points r and s is rotated over the angle \( \alpha_t \). This can be done in two basic ways: rotation and translation. In figure 4.4(a), points r and s are both on a lever which is rotated. Another option is rotating point r on a lever that rotates around point s. A displacement of point r in x-direction will result in the same action. This can be done by driving point r in x-direction but also by elongation of beam 2 or shortening of beam 1. Two actuators in the two upper bars is not an option because of the synchronization problems.

![Figure 4.4 - Two options for angle adjustment of bed using bar mechanism](image)
The length of the beams can be optimized. In figure 4.5(a) a mechanism with long beams and in figure 4.5(b) a mechanism with short beams is drawn. The beams are drawn in ambulance position (solid lines), in working position (dashed lines) and in anti-trendelenburg position (dotted lines). The bed is only drawn in the anti-trendelenburg position.

![Figure 4.5 - Difference between long and short beams in the mechanism](image)

The trendelenburg position enforces a rotation of $30^\circ$ of the beams independent of the length of the beams. The length of the beams in figure 4.5(b) is determined at such a length that a rotation of $30^\circ$ of the beams lifts the bed to working position. Because bending stiffness of a beam can be expressed as $c_{bending} = \frac{EI}{l^3}$ and axial stiffness as $c_{axial} = \frac{EA}{l}$, shorter beams result in a stiffer construction. A point of attention is the position of the bed because shorter beams result in a smaller distance between bed and undercarriage in trendelenburg and anti-trendelenburg position.

### 4.3 Main dimensions and loads on the mechanism

In order to dimension the mechanism, the forces acting on it will be determined as a function of several geometric parameters. These parameters are listed in table 4.1. A free body diagram of the mechanism can be seen in figure 4.6. The forces can be calculated using equilibria of forces and moments of all parts. This can be seen in appendix D. These forces can be expressed as a function of the load on the bed $F_l$.

Optimization of the mechanism can be performed. Analysis of the mechanism shows the following relationships:

- The arm of the load force depends on $x$. A smaller distance $x$ results in a smaller load on the bars.
- The larger the distance between the beams $a$, the smaller the loads on the bars and bearings.
- The longer the arms of the actuators $a_h$ and $a_t$ and the smaller the arms of the load (which means the length of the beams $l$), the smaller the forces needed to actuate the mechanism $F_{act,h}$ and $F_{act,t}$.
- The start angles of the mechanism shift the reach of the angles $\alpha_h$ and $\alpha_t$. Because the range of $\alpha_h$ is $<0^\circ, 30^\circ>$, $\gamma_h$ must be chosen 15 degrees, because this provides the largest arm during the stroke of the actuator.
- For the same reason, $\gamma_t$ must be chosen zero, because the range of $\alpha_t$ is $<-30^\circ, 30^\circ>$.
- $\delta$ will be chosen zero for the same reason.
Figure 4.6 - Forces on mechanism

<table>
<thead>
<tr>
<th>symbol</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_h$</td>
<td>Height angle (angle between horizontal and beam 1)</td>
</tr>
<tr>
<td>$\alpha_t$</td>
<td>Trendelenburg angle (angle between horizontal and bed)</td>
</tr>
<tr>
<td>$\gamma_h$</td>
<td>Start angle of height actuation</td>
</tr>
<tr>
<td>$\gamma_t$</td>
<td>Start angle of trendelenburg actuation</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Angle of line through $p$ and $q$ with respect to the bed</td>
</tr>
<tr>
<td>$F_{\text{act},h}$</td>
<td>Actuation force for height adjustment</td>
</tr>
<tr>
<td>$F_{\text{act},t}$</td>
<td>Actuation force for trendelenburg adjustment</td>
</tr>
<tr>
<td>$F_i$</td>
<td>Weight of patient on bed</td>
</tr>
<tr>
<td>$F_d$</td>
<td>Radial force on bearing in point $d$</td>
</tr>
<tr>
<td>$F_p$</td>
<td>Radial force on bearing in point $p$</td>
</tr>
<tr>
<td>$F_q$</td>
<td>Radial force on bearing in point $q$</td>
</tr>
<tr>
<td>$F_r$</td>
<td>Radial force on bearing in point $r$</td>
</tr>
<tr>
<td>$F_s$</td>
<td>Radial force on bearing in point $s$</td>
</tr>
<tr>
<td>$a$</td>
<td>Distance between points $p$ and $q$</td>
</tr>
<tr>
<td>$l$</td>
<td>Length of beams</td>
</tr>
<tr>
<td>$x$</td>
<td>Distance between rotation point of bed and load $F_l$</td>
</tr>
</tbody>
</table>

Table 4.1 - Explanation of symbols in figure 4.6
The optimized start angles $\alpha_h$, $\alpha_t$ and $\delta$ can be substituted in the equations for the forces (see appendix D). The results can be found in table 4.2.

<table>
<thead>
<tr>
<th>Force expression</th>
<th>$F_p$</th>
<th>$F_l \frac{L}{a} \cdot \frac{\cos \alpha_h}{\cos \alpha_t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_q$</td>
<td>$F_l \sqrt{\frac{x}{2\pi} \cdot \frac{\cos^2 \alpha_h}{\cos^2 \alpha_t} + 1 - 2 \cdot \frac{x}{a} \cdot \frac{\cos \alpha_h \sin \alpha_h}{\cos \alpha_t}}$</td>
<td></td>
</tr>
<tr>
<td>$F_{ax,1}$</td>
<td>$(\frac{x}{a}, \frac{\cos \alpha_h \cos 2\alpha_h}{\cos \alpha_t} + \sin \alpha_h)F_l$</td>
<td></td>
</tr>
<tr>
<td>$F_{tra,1}$</td>
<td>$F_l \cos \alpha_h$</td>
<td></td>
</tr>
<tr>
<td>$F_{act,h}$</td>
<td>$\frac{L}{a_h} \cdot F_l$</td>
<td></td>
</tr>
<tr>
<td>$F_{act,t}$</td>
<td>$\frac{x \cos \alpha_h}{\alpha_t \cos \alpha_t} \cdot F_l \frac{\cos (\alpha_h - \alpha_t)}{\cos \alpha_t}$</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2 - Expressions for forces acting on mechanism as a function of dimensions and $F_l$

The main dimensions are determined in order to calculate the normal load on axles, bars and bearings. The distance between the bars, $a$, is made as large as possible. The distance between the top of the box and the turning point of beam 1 is assumed to be 35 mm. The same distance is needed between the turning points of beam 2 and the bed. This bed is assumed to be 50 mm high. The total height of the patient in the ambulance can maximal be about the height of a table and is determined as 750 mm. $a$ is assumed 140 mm (see figure 4.7). The dimensions in the $y$-$z$ plane can also be considered. The bed is made 570 mm wide. Assuming 20 mm for the thickness of the rim of the bed, 530 mm is left under the bed. By placing the bed out of the middle of the undercarriage, a wider bed can be used without loosing sight on the equipment.

Figure 4.7 - Dimensions of mechanism

The load on the bed can be determined. The patient weighs 100 kg. A doctor could lean on the end of the bed or reanimate the patient. The load on the bed is applied as a force $F_l$ of 2000 N acting on the middle of the bed, so $x = 600$ mm. The formulas from table 4.2 are calculated in a spreadsheet for lifting the bed ($\alpha_h$ from 0 till 30°, $\alpha_t = 0$°), rotating to anti trendelenburg position ($\alpha_h = 30$°, $\alpha_t$ from 0 till $-30$°) and for rotating the bed to trendelenburg position ($\alpha_h = 0$°, $\alpha_t$ from 0 till 30°). The maximum value of the forces can be found in table 4.3.

<table>
<thead>
<tr>
<th>Force</th>
<th>$F_p$</th>
<th>$F_q$</th>
<th>$F_{q,x}$</th>
<th>$F_{q,z}$</th>
<th>$F_s$</th>
<th>$F_{s,x}$</th>
<th>$F_{s,z}$</th>
<th>$F_d$</th>
<th>$F_{d,x}$</th>
<th>$F_{d,z}$</th>
<th>$F_{ax,1}$</th>
<th>$F_{tra,1}$</th>
<th>$F_{act,h}$</th>
<th>$F_{act,t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>kN</td>
<td>10,1</td>
<td>10,3</td>
<td>10,1</td>
<td>2,0</td>
<td>37,8</td>
<td>37,7</td>
<td>2,0</td>
<td>25,6</td>
<td>25,6</td>
<td>4,0</td>
<td>10,1</td>
<td>2,0</td>
<td>27,6</td>
<td>15,4</td>
</tr>
</tbody>
</table>

Table 4.3 - Maximum forces
4.4 Design of the mechanism

The axles, bars and beams of the mechanism form four different junctions: two junctions at the side of the undercarriage and two at the bed-side, two with beam 1 and two with beam 2. We will first focus on the turning point with bearings s and d from figure 4.6. Because three parts rotate around each other, three different options can be found. They are listed in table 4.4.

| Option 1 | Rigid axle on undercarriage  
Bearings in beam 1  
Bearings in trendelenburg bar |
|----------|------------------------------------------------------------------|
| Option 2 | Bearings in undercarriage  
Rigid axle in beam 1  
Bearings in trendelenburg bar |
| Option 3 | Bearings in undercarriage  
Bearings in beam 1  
Trendelenburg bar on axle |

Table 4.4 - Three options for constructing turning points with s and d

Option 1 represents a rigid axle on the undercarriage. This could be an axle shaft that is mounted to the undercarriage and pushed through the bearings in beam 1 and the trendelenburg bar. In option 2, a ring is fixed to the undercarriage, where the axle in beam 1 rotates in and the trendelenburg bars rotate around. The forces $F_s$ and $F_d$ act on the same place on the axle, so the moment in the axle is relatively small. Furthermore, a rigid axle of this diameter is more stiff than an axle that must fit in a bush of that diameter. The distance between the bearings that support beam 1 is larger for option 2. To complete the possibilities, the trendelenburg bar could also be fixed on the axle.

Option 2 is the stiffest option, because it combines a relatively large diameter of the axle with a small moment in the axle.

The other turning point in beam 1 (q in figure 4.6) counts only two parts, beam 1 and the connection plate to the bed. The same options can be found now:

**axle shaft** An axle is fixed in a bush with bearings in beam 1. A relatively small diameter of the axis is needed to fit in beam 1.

**rigid axle in beam 1** The rigid axle in beam 1 sets the bearings on a larger distance and allows a stiffer axle. A way to mount and dismount the axle in the bearings is more difficult for this option.
For the other turning points (p and r in figure 4.6), bearings in beams 2 are chosen above bearings in the trendelenburg bars or in the connection plate and a rigid axle between the beams. Mounting and dismounting is easier, because the connection plate and the trendelenburg bars are mounted on the axle between the beams 2.

### 4.4.1 Bearings

Three types of bearings are represented in figure 4.8. Ball bearings (figure 4.8(a)) are commonly used in constructions, but require a lot of space. Needle bearings (see figure 4.8(b)) are relatively small in diameter and can handle high loads. These two types of bearing require seals against dirt and to keep the lubricant in the bearing. They cannot handle axial forces. Flanged bushes are slider bearings that can handle axial forces. They are very thin and therefore save space and weight.

![Figure 4.8 - Different types of bearings](image)

DU-B bearings consist of three bonded layers [3]: a bronze backing strip and a porous bronze matrix, impregnated and overlaid with PTFE/lead bearing material. The bronze backing provides high corrosion resistance, anti-magnetic properties and good thermal conductivity. This is combined with the dry bearing properties of PTFE and good wear resistance.

The combination of sliding speed and load determines the life of the bearings. However, a certain load is necessary to provide good sliding quality (see figure F.4 in appendix F). Furthermore, the axles may determine the diameter of the bearings when stiffness or strength is needed. In table 4.5, the load on the bearings is found for the different bearings in points d, p, q and s. The load can be determined as:

\[
\bar{p} = \frac{F}{D_i B}
\]

The loads are divided over a number of bearings. For \(F_d\), \(F_q\) and \(F_q\) this number is 2, but for \(F_p\) the number of bearings is 4 because of axial retainment of beam 2.

![Table 4.5 - \(\bar{p}\) on DU-B bearings](image)

<table>
<thead>
<tr>
<th>Nominal Diameter</th>
<th>Flange-Diam.</th>
<th>Length</th>
<th>(\bar{p}) on bearing:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(D_i)</td>
<td>(D_o)</td>
<td>(D_{fl})</td>
</tr>
<tr>
<td>20</td>
<td>23</td>
<td>30</td>
<td>11</td>
</tr>
<tr>
<td>20</td>
<td>23</td>
<td>30</td>
<td>16</td>
</tr>
<tr>
<td>25</td>
<td>28</td>
<td>35</td>
<td>21</td>
</tr>
<tr>
<td>30</td>
<td>34</td>
<td>42</td>
<td>16</td>
</tr>
<tr>
<td>30</td>
<td>34</td>
<td>42</td>
<td>26</td>
</tr>
<tr>
<td>35</td>
<td>39</td>
<td>47</td>
<td>26</td>
</tr>
<tr>
<td>40</td>
<td>44</td>
<td>53</td>
<td>26</td>
</tr>
<tr>
<td>45</td>
<td>50</td>
<td>58</td>
<td>26</td>
</tr>
</tbody>
</table>
Bearings s and d have to fit around each other. Bearing d has to be the outside bearing, so a combination of bearing 45-50-58 for d and 30-34-42 is possible, as well as a combination of 40-44-53 with 25-28-35. For bearing p and q, the bearings are large enough. The diameter of the axle may be the issue here. Therefore, the dimensions of the axle will first be determined before a definitive bearing choice is made.

4.4.2 Axle s in beam 1

A hollow axle combines light weight and high stiffness because of the large distance between the outer fibres. In order to find an easy to make and cheap axle, a standard thick walled tube will be chosen as a base of the axle. Standard dimensions of thick walled tubes can be found in literature \[4\]. The diameter of the axle must be large enough to provide a counter face for the flange of the bearing. This requires a relatively large wall thickness.

When the part of the axle with the smaller diameter (for the bearing) is constructed as an apart axle which is screwed against another axle, the notch effect does not occur and a hollow axle can be used. A lighter construction can be build.

Bending stress in a rigid axle can be seen as a combination of tension and compression at the outer fibres of the axle (see figure 4.9(a)). Because the axle is build up from two different parts, tension cannot occur on the interface between the two parts. When a normal stress $\sigma_d$ (as large as the maximum bending stress $\sigma_b$) is applied by pulling the one part to the other, no positive stress is present (see figure 4.9(c)). In order to have a constant and defined compression stress, a bolt with some length is needed.
Forces acting on the axle and parameters used for the calculation can be found in figure 4.10.

Due to the fact that the bearings cannot be mounted in line with the plates of beam 1, a moment is applied on the axle in beam 1. The line of the moment and the forces can be seen in figure 4.10(a). The maximal moment in the axle is marked $M_b$, the moment at the place where the diameter is reduced is called $M_d$ (see figure 4.10(a)). The distance of these places with respect to the line of action of the force on the bearing are called $x_b$ and $x_d$, respectively. The second moment of area of a hollow axle with outside diameter $D_o$ and inside diameter $D_i$ is defined as

$$I = \pi \left( D_o^4 - D_i^4 \right) / 64$$

and its section factor for bending is defined as

$$W = \frac{I}{e} = \frac{\pi \left( D_o^4 - D_i^4 \right)}{32D_o}.$$ 

The bending stress is defined as

$$\sigma_b = \frac{M}{W}.$$ 

The moments $M_b$ and $M_d$ and bending stress at these positions can be expressed:

$$M_b = F \cdot x_b \quad \quad W_{b,b} = \frac{\pi (D_{a,o}^4 - D_{a,i}^4)}{32D_{a,o}} \quad \quad \sigma_{b,b} = \frac{M_b}{W_{b,b}}$$

$$M_d = F \cdot x_b \quad \quad W_{b,d} = \frac{\pi (D_{b,o}^4 - D_{a,i}^4)}{32D_{b,o}} \quad \quad \sigma_{b,d} = \frac{M_d}{W_{b,d}}$$

In table 4.6, the bending stress is calculated for several dimensions. These calculations are based on the following assumptions:

$$F = \frac{1}{2} F_r = 19 \text{ kN}$$
$$E = 2,10 \cdot 10^5$$
$$x_d = 14 \text{ mm}$$
$$x_b = 25 \text{ mm}$$

The dimensions of the axle are chosen to fit the commercially available thick walled tubes of st. 52 [4]. The yield stress of this material is 430 N/mm$^2$.

The axle will be made of the thick walled tube 51-23 and bearing 30-34-42 will be applied. In order to provide only compression in the axle, a surface pressure of 153 N/mm$^2$ must be applied. This requires a force in the bolt:

$$F_{\text{bolt}} = \sigma_d \cdot \frac{1}{4} \cdot \pi (D_{b,o}^2 - D_{a,i}^2)$$

For this dimension, the force in the bolt is 44,5 kN, which can be delivered by a M16 inbus bolt, where the maximum force is 138 kN for bolts of highest quality [5].

The deflection of the axle can be computed using a simple finite element model (see figure 4.11). A cantilever beam that represents the half of the axle is drawn in ALGOR. The total displacement...
4.4. DESIGN OF THE MECHANISM

<table>
<thead>
<tr>
<th>Dimensions of axle</th>
<th>Geometrical properties</th>
<th>Bending stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{a,o}$</td>
<td>$D_{a,i}$</td>
<td>$D_{b,o}$</td>
</tr>
<tr>
<td>[nm]</td>
<td>[mm$^4$]</td>
<td>[mm$^3$]</td>
</tr>
<tr>
<td>38</td>
<td>18</td>
<td>25</td>
</tr>
<tr>
<td>44,5</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>18,0</td>
<td>2,72</td>
<td>8,09</td>
</tr>
<tr>
<td>25,2</td>
<td>2,48</td>
<td>10,4</td>
</tr>
<tr>
<td>24,3</td>
<td>1,59</td>
<td>10,1</td>
</tr>
<tr>
<td>31,8</td>
<td>2,60</td>
<td>12,5</td>
</tr>
<tr>
<td>31,0</td>
<td>1,73</td>
<td>12,1</td>
</tr>
<tr>
<td>29,7</td>
<td>0,504</td>
<td>11,7</td>
</tr>
</tbody>
</table>

Table 4.6 - Bending stress in axle s in beam 1

of beam 1 with respect to the fixation of the bearings, due to the deflection of the axle is $0,068 - 0,044 = 0,024$ mm when a force of 20 kN is applied.

![Figure 4.11 - Deflection of axle s in beam 1](image)

4.4.3 Axle q in beam 1

The axle at the other side of beam 1, marked with q in figure 4.6, is loaded with $F_q$. One could choose for symmetry and use exactly the same axle as axle q. But because the connection plate between the bed and the axles in beam 1 and 2 is different than the trendelenburg bar at the other side. Furthermore, beam 1 is already a-symmetric due to the height adjustment. Because this turning point does not have to fit in another bearing, more freedom of choice can be found here. The same calculation is performed as in section 4.4.2 with the following parameters:

\[
F = \frac{1}{2} F_q = 5,2 \text{ kN}
\]
\[
E = 2,10 \cdot 10^5
\]
\[
x_d = 10 \text{ mm}
\]
\[
x_b = 16 \text{ mm}
\]

Results can be found in appendix E.

The bearing used in the connection plate must be as small as possible in order to reach a certain surface pressure (see table 4.5) and to make the connection plate as small as possible. Bearing 20-23-30,5 can be delivered with a length of 11,5 mm and 16,5 mm, bearing 30-34-42,5 with a length of 16 mm, but all other sizes can only be delivered with a length of 21 mm. Therefore, bearing 30-34-42,5 is chosen, to keep a reasonable diameter for the axis. A thick walled tube 44,5 x 22,5 mm is used for the middle part of the axle.
In order to have only compressive stress on the interface between two parts of the axle, a force of
\[ F_{\text{bolt}} = \sigma_d \cdot \frac{1}{4} \pi (D_{b,o}^2 - D_{a,i}^2) = 29 \text{ N/mm}^2 \cdot \frac{1}{4} \pi (30^2 - 22.5^2) = 900 \text{ kN} \]
is needed. An M8 bolt is used for that purpose, which maximum force is 31 kN.

### 4.4.4 Beam 1

Turning points is assumed to be 35 mm above the top plate of the undercarriage. When this axle is constructed in the middle of the beam, maximal 70 mm of height can be reached. Because there is more space between the the two other beams, a rather high and therefore stiff and light beam can be constructed in this space. Note that the axial stiffness of a beam is only about one quarter of the original stiffness when it is not attached in the neutral axis.

Because the tendelenburg axle rotates above beam 1, the height of beam 1 is limited. When beam 1 is beveled, beam 1 can have full height in the middle. Figure 4.12 shows beam 1 and beam 2 of the mechanism in three different positions.

![Figure 4.12 - Trendelenburg positions require beam 1 to be beveled](image)

Making a suitable profile by bending steel sheet material is an option that leaves more freedom to design with respect to standard squared or rectangular tubes and is relatively cheap. In figure 4.13 a cross-section of beam 1 can be seen.

![Figure 4.13 - Cross-section of beam 1](image)
4.4. DESIGN OF THE MECHANISM

Beam 1 can be produced from 2 bent U-plates (1) that connect the lower (2) and upper plate (3) of the beam. With this construction, most material is at the outer fibre. The ends of the bent U-plates are cut in and folded under an angle to bevel the beam and leave space for the trendelenburg axle. The two U-formed plates are aligned together with the plates for height adjustment (4) and holes for the axles can be drilled. The axles (the axle is one millimeter larger in diameter between the plates) are now fit in between the plates. The bottom plate (2), with two rectangular slits in it for the height adjustment, can be welded to the U-formed plates. The ends of the U-formed plates and the bottom plate are welded together and spotwelds are used to connect the plates near the vertical part of the U-formed plate.

The torsion stiffness of the end of beam 1 is increased by closing the beam with a bent plate (6). This plate is bent 90°. The bent part is now upright in the fold of the upper plate (3).

The plate for height adjustment fits through the rectangular holes in the bottom plate. They can be mounted in the upper plate using the same construction as in the wheels with merlons 3.4(b) on the plate for height adjustment and rectangular holes cut (e.g. laser cut) in the upper plate. The plates are bend together to form a small distance between the plates where the actuator can be fixed. In order to prevent buckling of these plates, the height adjustment plate must be stiffened by adding a U-formed plate (5) that provides stiffness in the x and z-direction or, in other words, prevent the plates for bending together.

When the angle of the height adjustment plates is (smaller than) 40° with respect to the vertical axis, the hole in the plates can be drilled in the horizontal part of the height adjustment plate. A ring is mounted in the hole for the pin through the cylinder to lower the surface pressure from the force and to provide more stiffness perpendicular to the plate around the hole. When a plate with a thickness of 2 mm is used, the stress would be \( \sigma_s = \frac{F}{A} = \frac{28 \text{ kN}}{2 \text{ mm}} = 280 \text{ N/mm}^2 \), which is lowered by the ring to 95 N/mm² on the ring.

The pin through the eye of the actuator cannot fall out of the hole because of the rim at one side and a split pin at the other side.

The construction of the height adjustment is closed by the lower plate of beam 1 and can be closed at the underside and back by a plate that is folded around the plates and connects to the partition between the torsion stiffeners (see the drawing of beam 1 in appendix I).

The inner square of beam 1 could be filled with foam to provide more stiffness to the plates and prevent noise production. The space at the outsides can be used to fix cables and tubes and guide them to the connection board on the bed.

In order to dimension the beam, we take a look at the stiffness and strength. The deflection \( f \) at the end of a beam can be expressed as:

\[
 f = \frac{F l^3}{3 E I} \tag{4.3}
\]

Figure 4.14 - Deflection \( f \) of a beam under load \( F \)

Let us assume a deflection of maximum 1 mm under a load of 1 kN. The stiffness of beam 1 can be characterized by the term \( E I \), which must be \( E I = \frac{3F l^3}{1000} = 3 \cdot 10^{11} \text{ N mm}^2 \)

A construction as in figure 4.13 of steel \( (E = 2, 1 \cdot 10^9 \text{ N/mm}^2) \), outside dimensions of 230 mm x 140 mm and plate thickness of 1 mm results in \( EI = 6,3 \cdot 10^{11} \text{ N mm}^2 \).

When a beam is stiff enough, the strength is usually not a problem. The maximum stress in the beam can be expressed as:

\[
 \sigma_{\text{beam } 1} = \sigma_b + \sigma_t = \frac{M_b}{W_b} + \frac{F_{ax,1}}{A_{\text{beam } 1}} \tag{4.4}
\]
where $\sigma_b$ is the bending stress, $\sigma_t$ is the tension stress, $M_b$ is the bending moment, $W_b$ is the section factor for bending and $A_{beam_1}$ is the area of the cross section of beam 1. The bending moment is introduced by the load acting on the end of the beam and the fact that $F_{tra,1}$ does not act in the middle of the beam but on a distance of 38 mm.

$$M_b = F_{tra,1} \cdot l + F_{ax,1} \cdot 38 = 2 \text{kN} \cdot 1200 \text{mm} + 10 \text{kN} \cdot 38 \text{mm}$$ (4.5)

$$\sigma_{beam_1} = \frac{2780 \text{Nm}}{4.2 \times 10^4 \text{mm}^3} + \frac{10.1 \text{kN}}{936 \text{mm}^2} = 66 + 11 \text{N/mm}^2 = 77 \text{N/mm}^2$$ (4.6)

The load can almost be multiplied by 5 until the yield stress is reached. The total stiffness of the mechanism will be computed in section 4.6.

### 4.4.5 Axle r in trendelenburg bar

The axle in the trendelenburg bar can be dimensioned as well. The two trendelenburg bars and the bed will add torsion in the axle when the two sides are not equally loaded. In order to calculate the torsion and rotation angle, the following equations are listed:

$$I_p = \frac{\pi (D_{a,o}^4 - D_{a,i}^4)}{32}$$ (4.7)

$$W_p = \frac{\pi (D_{a,o}^4 - D_{a,i}^4)}{16D_{a,o}}$$ (4.8)

$$\sigma_p = \frac{M_p}{W_p}$$ (4.9)

$$\phi_p = \frac{M_p \cdot l}{G \cdot I_p}$$ (4.10)

with the following assumptions:

$$F = \frac{1}{2} F_p = 5.1 \text{kN}$$

$$E = 2 \times 10^5$$

$$x_d = 32 \text{mm}$$

$$x_b = 95 \text{mm}$$

$$l = 275 \text{mm}$$

$$M_p = 2.5 \text{kN} \cdot 137 \text{mm}$$

the bending stress, torsional stress and rotation angle can be calculated. Results are represented in table E.2 in appendix E.

The compromis between a large and stiff axle and some surface pressure on the bearings can best be made by choosing bearing 30-34-42, because it can be delivered with a width of 16 mm. In order to provide torsional stiffness, a large outer diameter is chosen for the middle part of the axle. Because the outer diameter determines the beveling of beam 1 and the inner diameter has to be large enough in order to connect the end of the axle, thick walled tube 51-23 is chosen.
4.4.6 Beam 2

Only axial loads can be applied to beam 2. Buckling may occur when an axial pressure load is applied. The buckling force can be expressed as a function of the \( EI \) of the beam and the buckling length which equals \( 2l \).

\[
F_k = \frac{\pi^2 EI}{l_k^2}
\]

(4.12)

When the beam is rectangular, the direction of buckling is known. Buckling of beam 2 in \( z \)-direction is preferred, because this failure will not load the axles \( r \) and \( p \). The axial load on one beam is \( 5 \, kN \) because this is half the force \( F_{ax,1} \) from table 4.3. Assuming a safety factor of 5, the buckling force \( F_k \) may be \( 25 \, kN \). The required \( EI \) for beam 2 can now be determined.

\[
EI = \frac{F_k l_k^2}{\pi^2} = \frac{25000(2 \cdot 1200)^2}{\pi^2} = 1,46 \cdot 10^{10} \, Nmm^2
\]

(4.13)

When a steel rectangular tube of \( 55 \times 50 \times 1 \) is used, \( EI = E \frac{BH^3-bh^3}{12} = 2,1 \cdot 10^5 \cdot \frac{55 \cdot 50^3 - 53 \cdot 48^3}{12} = 1,77 \cdot 10^{10}, EI = 1,43 \cdot 10^{10} \, Nmm^2 \) is reached when a wall thickness of \( 0,8 \, mm \) is used. A wall thickness of \( 0,8 \, mm \) is enough.

Because only pressing forces act on these beams, the bushes for the bearings can be welded to the beam without high demands on the welding. The bushes can be welded to the beams at two sides. The bushes are a millimeter wider than the width of the rectangular tube, so they can be welded along the half of the diameter of the bush. When the bushes are welded, the beams are laid parallel to each other. The holes in the bushes can be drilled in one time for the two beams to create parallel holes. The position and direction of the holes is determined by this action. Finishing may occur for all holes apart. This treatment is only necessary for mounting of the bearings, so not the whole depth needs finishing. Boring and finishing in one time is also possible, so the inner diameter of the bush is constant through the depth of the holes.
4.5 Drive of mechanism

4.5.1 Parallelogram for displacement of trendelenburg actuator

The arm $a_h$ for the height adjustment is as long as $a_t$ in the calculation of forces. This determines the position of the actuators in the undercarriage and the stroke of the actuators. Because the trendelenburg bars rotate besides beam 1, this actuator must be the lowest one in the undercarriage, or two actuators must be used to drive the two trendelenburg bars. Synchronization problems may occur, then.

With help of a parallelogram, the actuation force can be displaced. The actuator for the trendelenburg angle may now fit under the actuator for the height adjustment, so a smaller actuator compartment is needed. This can be seen in figure 4.16.

![Figure 4.16 - Actuation of trendelenburg adjustment](image.png)

The actuation force $F_{act,t}$ acts on the trendelenburg actuation body. Because this force acts on the body and not directly to the trendelenburg bar, a moment acts on the trendelenburg body. The actuation guidance prevents rotation of the body. The equilibrium of moments on the actuation body can be written as:

$$F_{act,t} \cdot l_a = F_g \cdot l_g \rightarrow F_g = \frac{F_{act,t} \cdot l_a}{l_g}$$

(4.14)

The design of the actuation body depends on the choice of the actuators and will be subject of section 4.8.

4.5.2 Actuator choice

Several actuator types are considered.

- electric
- hydraulic
- pneumatic

For optimal ease of use, no hand operated system is used. The forces needed to actuate the height and trendelenburg adjustment are about 28 and 16 kN, respectively. A stroke of 50 mm is needed for the height actuation and 100 mm for the trendelenburg adjustment.

Electric spindles are not strong enough to deliver the forces needed. Smaller actuation forces can be reached when longer arms are used, but this requires more space in the undercarriage and longer strokes of the actuators. Hydraulic actuation can be used. An actuation force of...
27.6 kN could be made with a pressure of 200 bar on a circular surface with a diameter of 42 mm:

\[ D = \sqrt{\frac{F}{p \cdot \frac{1}{4} \pi}} = \sqrt{\frac{27.6 \, kN}{200 \times 10^5 \, N/m^2 \cdot \frac{1}{4} \pi}} = 0.042 \, m = 42 \, mm. \]

Pneumatic actuation is not an option because of the low stiffness and force density.

For hydraulic actuation of the mechanism, cylinders and a pump are needed. When oil is under high pressure, the highest stiffness can be reached, but when a maximum pressure of 200 bar is used, affordable and commercially available cylinders and pumps can be used [6].

The area needed to deliver the actuation force \( F_{act,h} \) is 13.5 cm\(^2\). The same calculation can be made for the actuation of the trendelenburg adjustment. An area of 8 cm\(^2\) is found.

As a guideline for the dimensions of the cylinders, the catalogue of A4 Hydraulics [7] is used. At each side of the cylinder, bearing supports are used, referred to as mounting style K/K in literature.

The cylinders ACD-40 and ACD-50 are used, with piston area of 12.6 and 19.6 cm\(^2\) respectively. The dimensions of these cylinders can be seen in figure 4.17.

![Figure 4.17 - Dimension of hydraulic cylinders](image)

<table>
<thead>
<tr>
<th>Type</th>
<th>area [cm(^2)]</th>
<th>Dimensions [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACDK/K-40</td>
<td>12.6</td>
<td>R3/8 206 50 41 50 25 30 20 19 24 48 67 12</td>
</tr>
<tr>
<td>ACDK/K-50</td>
<td>19.6</td>
<td>R3/8 235 60 46 55 28 35 25 23 29 57 75 15</td>
</tr>
</tbody>
</table>

Table 4.7 - Dimensions of hydraulic cylinders

The hydraulic control scheme is shown in figure 4.18.

![Figure 4.18 - Schematic drawing of hydraulic system](image)

The pump P pumps oil from the reservoir O to the switch block S. When the switch block is in position 1, the oil flows to the cylinder which results in translation of the piston. When the required height or angle is reached, output 2 can be chosen, where the cylinder is locked. By placing the valve as near as possible to the cylinder, thus minimalizing the volume under pressure,
a high stiffness can be achieved. Output 3 of the switch block results in flowing back of the oil from the cylinder. In order to make this happen in a controlled way, an extra restriction R can be build in.

4.5.3 Pump

When the cylinder for the height adjustment is filled completely, the volume of the cylinder is filled over a length of the stroke s. The volume V can now be calculated as \( V = A \cdot s = 19.6 \, \text{cm}^2 \cdot 5 \, \text{cm} = 98 \, \text{cm}^3 \). This volume must be filled in maximal 10 seconds. The pump rate must be minimal 1180 \( \text{cm}^3/\text{min} \). A small pump from Oleodinamica and (available at Breedveld-Weaver) can bring up maximal 0.17 \( \text{cm}^3/\text{rev} \) at a maximal number of revolutions of 9000 \( \text{rev/min} \). A maximal flow of 0.17 \( \text{cm}^3/\text{rev} \cdot 9000 \text{ rev/min} = 1530 \, \text{cm}^3/\text{min} \) can be reached with this pump at a maximum working pressure of 220bar.

The power needed to lift the bed can be calculated by the movement of the cylinder. The power can be calculated by dividing the amount of work \( W \) by the time in which the work is done. \( W = F \cdot s = \frac{27.6 \, \text{kN}}{50 \, \text{mm}} = 300 \, \text{W} \). The pump is accompanied by a 800 W DC Motor that works on 12 or 24 Volt. A reservoir is deliverable from 1 liter (1000 \( \text{cm}^3 \)). This is enough to fill the two cylinders, because this volume is \( V_{\text{cyl}} = A \cdot s = 19 \cdot 5 + 12 \cdot 10 = 224 \, \text{cm}^3 \). When an oil feed line of 1 m and a diameter of 2 cm are assumed, a volume of \( V_{\text{tube}} = \frac{1}{4} \pi D^2 l = 315 \text{cm}^3 \) is needed to fill the tubes. The reservoir of 1 liter is enough for this application, because the actuation is only used a few times a week when transport takes place. Further characteristics can be found in literature: [6] and [8].

4.6 Stiffness of the mechanism

![Figure 4.19 - Stiffness of the bed in z-direction](image)

The stiffness of the bed in z-direction \( (c_z) \) depends mainly on two stiffnesses: the stiffness of the actuator \( (c_{\text{act},h}) \) and the bending stiffness of beam 1 including the axle in beam 1 and the height adjustment plates \( (c_{\text{beam1},z}) \). The stiffness \( c_{\text{beam1},z} \) is investigated with Algor:

![Figure 4.20 - Stiffness of beam1 in z-direction](image)

\[
c_{\text{beam1},z} = \frac{F}{dz} = \frac{2000 \, \text{N}}{3.15 \, \text{mm}} = 6.3 \cdot 10^2 \, \text{N/mm} \quad (4.15)
\]
The stiffness of the actuator is estimated on basis of the volume of the cylinder and the stiffness of the oil. The compressibility $\kappa$ of oil is $500 \cdot 10^{-12} \cdot 800 \cdot 10^{-12} \ Pa^{-1}$. The modulus of elasticity $E$ is $1/\kappa = 1,25 \cdot 10^3 \ N/mm^2$ which is $1/170$ of the stiffness of steel. Because the cylinder and the seals are not perfect, a stiffness 200 times as low as steel is assumed. The length of the cylinder for calculation is 100 mm. The oil in the oil feed line is not taken into account.

$$c_{act,h} = \frac{EA}{l} = \frac{2,1 \cdot 10^5 \ N/mm^2 \cdot 200 \cdot 1960 \ mm^2}{100 \ mm} = 2,1 \cdot 10^4 \ N/mm \quad (4.16)$$

The total stiffness in z-direction $c_z$ can now be calculated using the stiffness of the actuator $c_{act,h}$, stiffness of the beam $c_{beam1,z}$ and the transmission ratio for the actuator $i = \frac{1200}{90}$.

$$\frac{1}{c_z} = \frac{1}{c_{act,h}/i^2} + \frac{1}{c_{beam1,z}} = \frac{1}{2,1 \cdot 10^4 / (90)^2} + \frac{1}{6 \cdot 3 \cdot 10^2} \rightarrow c_z = 1,0 \cdot 10^2 \ N/mm \quad (4.17)$$

When the bed leans on the actuator, the bed will lower one centimeter for every 100 kg loaded on the bed, assuming an infinite stiff bed.

The rotational stiffness can be calculated using the stiffness of beam 1 and axles, $c_1$, and the combined stiffness of beam 2, axles and actuator, $c_2$. A schematic drawing can be found in figure 4.21.

$$k = M \phi = \left( \frac{1}{c_1} + \frac{1}{c_2} \right)^2 \quad (4.18)$$

$c_1$ is investigated with ALGOR. A force of 10 kN is acting on both sides of axle q, which is held on its place by axle s.

$$c_1 = c_{beam1,ax} = \frac{F}{dx} = \frac{20 \ kN}{0,22 \ mm} = 91 \cdot 10^3 \ N/mm \quad (4.19)$$
Stiffness $c_2$ can be calculated from the stiffness of axle p and r, beams 2, trendelenburg bar and actuator for trendelenburg adjustment (see figure 4.23).

The stiffness of spring $c_2$ in figure 4.21 can be defined as:

$$\frac{1}{c_2} = \frac{1}{c_{act,t}/l^2} + \frac{1}{c_{axle,p}} + \frac{1}{c_{axle,r}} + \frac{1}{2c_{beam2}}$$

(4.20)

The stiffness of the actuator can be calculated:

$$c_{act,t} = \frac{EA}{l} = \frac{2,1 \cdot 10^5 / 200 \cdot 1260}{200} = 6,6 \cdot 10^3 \text{ N/mm}$$

(4.21)

The stiffness of axle p, $c_{axle,p}$, is investigated with ALGOR (see appendix E).

$$c_{axle,p} = c_{axle,r} = \frac{F}{f} = \frac{10,1 \text{ kN}}{0,12} = 8,4 \cdot 10^4 \text{ N/mm}$$

(4.22)

The stiffness of beam 2 can be determined as:

$$c_{beam2} = \frac{EA}{l} = \frac{2,1 \cdot 10^5 (55 \cdot 50 - 53,4 \cdot 48,4)}{1200} = 2,9 \cdot 10^4 \text{ N/mm}$$

(4.23)

This results in a total stiffness $c_2$ of

$$\frac{1}{c_2} = \frac{1}{6,6 \cdot 10^3 / 137^2} + \frac{1}{8,4 \cdot 10^4} + \frac{1}{2,9 \cdot 10^4} + \frac{1}{2 \cdot 8,4 \cdot 10^4} \rightarrow c_2 = 2,6 \cdot 10^3 \text{ N/mm}$$

(4.24)

The rotational stiffness on the bed can be calculated:

$$k = \frac{M}{\phi} = \left(\frac{1}{\frac{1}{91 \cdot 10^3} + \frac{1}{2,6 \cdot 10^7}}\right) \cdot 137^2 = 47 \cdot 10^6 \text{ Nmm/rad}$$

(4.25)

The transmission ratio between deflection of the bed and the rotation of the bed is the distance between the rotation point and the actuation point of the load ($x$ in figure 4.6). In the middle of the bed, the stiffness is $k/i^2 = 47 \cdot 10^6 / 600^2 = 130 \text{ N/mm}$. At the end of the bed ($x = 1600 \text{ mm}$), the stiffness in z-direction is $20 \text{ N/mm}$.

In this calculation, the stiffness of the bed and the connection plate are not considered. Again, the stiffness is very much influenced by the stiffness of the actuator. A clamp that holds the trendelenburg adjustment instead of the actuator could raise this stiffness. For example, when the stiffness of the actuator $c_{act,h}$ is changed for the stiffness of two steel rods ($D = 10 \text{ mm}$), the stiffness in z-direction in the middle of the bed is $6,5 \cdot 10^2 \text{ N/mm}$ and 90 N/mm at the end of the bed. Furthermore, the bed can be fixed to the console or rest on a rod when the bed is in working position. The stiffness in y-direction can be increased by lifting the bed between the console. This will also prevent leaning on the bed at the end.
4.7 Fixation of mechanism

When a crash occurs, the hydraulic cylinders are not suitable for fixation of the mechanism in a crash, because of the high transmission ratio and their relatively low stiffness. Figure 4.24 shows the three different transport positions.

When the bed is in transport position, beam 1 could be fixed to the undercarriage using a lock. This lock is presented in figure 4.24(a) as a hook. The rotation of the bed is prevented with a cable or a hook at the end of the bed. The fixation of the mechanism in the trendelenburg position (see figure 4.24(b)) can be done in the same way. Fixation of the bed can perfectly be done with a safety belt. The belt tightener makes sure the belt is long enough for the preferred position of the mechanism, but when a crash occurs, the belt tightens and prevents rotation of the bed. When a backward crash occurs, the bed will slightly rotate to the horizontal position enforcing the oil in the trendelenburg hydraulic actuator to flow back.

Figure 4.24 - Fixation of mechanism
4.8 Final design

In this section, the final design of the turning points is explained. In figure 4.25, a section of the mechanism is made through the points r and s, when the bed is in ambulance position. The height adjustment plates are sectioned through the turning point. The axles are only partly sectioned. Scale 1:4 is used.

![Figure 4.25 - Section of mechanism through points r and s](image)

The production of beam 1 is explained in section 4.4.4.

Before fixing axle s in beam 1, a prop is welded in the thick walled tube. In the center of the tube, a hole is drilled in the prop and threaded. After fixing the thick walled tube (A) in beam 1, the bearing surface (C) can be screwed to the tube with an inbus bolt (D). The mounting ring to the undercarriage (E) with bearing s in it can be shifted on the bearing surface of axle s (C). The trendelenburg bar contains a ring (F) with bearing d in it. The trendelenburg bar is a folded box in a "wybert" form which contains two rings (one for bearing d and one for bearing e) and an open form to catch axle r. This form is formed like the line of moments on the bar. The bar is made from two plates with four bent rims. On one part, the rims are bend back, so a connection between the two parts can be made. First, the rings are laid in the holes and the two plates are fixed on it. The plates can be welded together where the connection between the upper and lower half is important because of the torsional stiffness. The rings can be welded along the diameter. The final diameter that acts as bearing surface can be bored last, the two bars at a time in order to create parallel axes. The construction drawing of the trendelenburg bar can be found in appendix I.

A side view of the mechanism can be seen in figure 4.26(a).

The trendelenburg actuation body is mounted in the trendelenburg bars. The trendelenburg actuator and the actuation guidance are mounted on the same axle. The actuation guidance is mounted with two bearings on an axle between the plates besides the mechanism. This guidance has a triangular form, so the bearings are wide away from each other and the actuation body is fixed in the y-direction. The actuation body is guided between the plates of the mechanism. Glider bearing material is brought on the actuation body for that purpose.

Axle r is constructed in the same way as axle s. When axle s is mounted in beam 1 and the mounting ring to the undercarriage (E) and the trendelenburg bars are mounted on it, the trendelenburg bars can be welded to axle r, where they lay against the rim in axle r. The whole construction can be
mounted in the undercarriage by mounting the fixation ring (G) to the ring to the undercarriage. This ring can be mounted to the plates in the undercarriage (G). The distance between the plates is determined by ring I. When maintenance is needed, or bearings needs changing, dismounting the fixation ring and pull it out a little, space to lift the whole construction out of the box is present. Screw thread in the bearing surfaces can be used to pull this part of the axle apart from the thick walled tube.

The construction drawing of the axles s and r can be found in appendix I. The final design of turning points p and q can be seen in figure 4.27.

The construction of the turning points p and q makes use of the same principles as the turning points in r and s. Construction drawings of the axles can be found in the appendix I.
Chapter 5

Bed

When further investigation of the patient is needed on arrival in the tertiary center, x-rays of the cervix (1), thorax (2), pelvis (3) and the spinal column (4) (see figure 5.1) are taken.

![Figure 5.1 - X-rays](image)

X-rays are send through the patient and caught with a receiver or on a film. Such a film could be lying under the matrass or in the bed. A large chamber for the film weakens the bed. When using a receiver, even motion pictures could be made. Because the receiver is placed under the bed or even under the mechanism for some pictures, the axles s and r and the beams disturb the x-rays. Therefore, the bed can be taken apart from the mechanism. The bed may not contain steel or hard plastics in the area where x-rays must be taken. Furthermore, reinforcements on the bed would disturb the x-rays, too.

A first guess for a cross section of the bed could look like figure 5.2:

![Figure 5.2 - Cross section of the bed](image)

Space for the mechanism is present under the bed and the rim does not prevent sight on the equipment. The matrass lies on the bed, between the rims. Such a matrass is about 70 mm high.
The height of the rim of the bed is 65 mm, so the mattress can be taken out of the bed without problems. The bed is made from epoxy fiber composite and foam in order to create light and stiff bed and to be able to make x-rays of the patient lying on the bed. The bending stiffness of this form can be calculated. The $I_z$ of this form is $1.6 \cdot 10^7 \text{mm}^4$. The modulus of the fibers is $25 \cdot 10^4 \text{N/mm}^2$ [9]. When a load of 100 kg is loaded on the middle of the bed (600 mm from the mounting point), the deflection at the end of the bed is 0.02 mm. When this load kg acts at the end of the bed, the bed deflects 0.34 mm.

Before the design of the bed is discussed in further detail, we will have a look at the fixation of the patient (section 5.1), fixing the mattress on the bed (section 5.2) and fixation of the bed on the connection plate (section 5.3).

### 5.1 Fixation of patient

To fixate the patient on the bed, the patient is laid on a mat (C) which is the mattress or an apart mat fixed under the bed with velcro (see figure 5.1). No difficult actions are needed to fixate the patient, the patient can easily be lifted on the bed and fixated. Strips with velcro (B) are made on both sides of this mat. One side has the velours side of the velcro on the strips, the other one the crochet side. These strips are brought to the front of the patient and fixated together. Two strips are layed over the shoulders and fixed on a strip over the middle of the patient. Because a lot of strips are present, a couple of strips can be loose, for example where an infusion is needed or where the patient is wounded. The legs are fixated apart from each other. These strips are fixated to the mat between the legs. Maybe three or different mats are made to supply a suitable fixation for patients of all sizes.

![Figure 5.3 - Fixation of the patient](image)

These strips are perfectly suited to fixate the patient in z-direction, but when a crash occurs, forces on the patient act in x-direction. Two blocks (D) are on both sides of the head. In a crash, the patient is pushed in the blocks. These blocks can be fixed on the mat (C) or on a separate mat that can be fixed under the mattress with velcro. The strips (B) make sure the patient will hit the blocks and stay on the bed. The blocks (D) will also prevent rotation of the head. Holes in the blocks will leave the ears open, which is more pleasant for the patient.

Is velcro strong enough to hold the patient in a crash? The velcro is fixed on the whole mat. An area of 180 cm x 50 cm can easily be created. A 20 g crash results in a force of 20 kN acting on the patient. The minimum shear strength of velcro must be $F_A = \frac{20 \text{ kN}}{180 \cdot 50 \text{ cm}^2} = 2.2 \text{ N/cm}^2$. Because the shear strength of velcro is 10 N/cm² [10], fixation of the mat with velcro can be done.
5.2 Fixing the matrass on the bed

The matrass must be fixed to the bed. The first option is presented in figure 5.4(a).

Figure 5.4 - Fixation of the matrass on the bed

A round thread (B) is fixed to the matrass or on a strip to the matrass (A). This thread can be threaded through the rail in the bed (C). The end of the bed must be open or the matrass is folded over the rim of the bed and threaded in the rail.

The matrass can also be fixed to the bed with strips. A few strips are stitched to the matrass, for example five in y-direction, divided over the length of the matrass and two in x-direction. This can be seen in figure 5.4(b).

The strips are stitched to the bed. The other end of the strips must be fixed to the bed. Five options for this problem can be found in figure 5.5.

Figure 5.5 - Four options for fixing of strips

(a): Figure 5.5(a) shows a way to fix the strips on the matrass (A) to the bed. The strip is threaded through the rim of the bed (B), where some corners are taken. A lot of friction is present when pulling the stip out of the bed. However, such a form is difficult to make in epoxy fiber composites.

(b): Option b (see figure 5.5(b)) is easier to make. For the upper slit in the bed, one jig is used, for the lower slit, two jigs from both sides must be used.

(c): Another mechanism than friction may be used. In figure 5.5(c), only two simple slits are made in the bed. The strips are laid around under the bed and connected to the bottom of the bed. An eye is made in the strip in the form of a key-hole (see figure 5.6). This eye is fixed over a hook (C) under the bed.

(d): When the strip is folded in a round chamber and a pin (D) is shoven into the rim of the bed. This locks in the strip and a rigid fixation is made. This option (see figure 5.5(d)) requires a separate part.

(e): When the locking is done with a clamp that is fixed to the bed, no parts could be lost (see figure 5.5(e)). The clamp (E) can rotate around an axle. Because clicking the clamp into the
hole requires bending out of the clamp, the strip is fixed. These last options require a lot from
the production proces of the bed and will result in an expensive bed.
Option (c) is chosen, because it is easy to make and no loose ends of the strips are present. The
matrass is not only fixated on friction between the bed and the strips, but also on the hooks under
the bed.

5.3 Fixation of the bed on the connection plate

5.3.1 Making space under the bed for making x-rays

When the transport team arrives at the tertiary center and further investigation is needed, making
the bed free from the mechanism must be very easy, without lifting of the bed. The acts needed
before x-rays could be taken are listed.

1. Lift the bed with the mechanism.

2. Support the bed with two hooks at the console and two rods to the undercarriage (see figure
5.7(a)).

3. Remove the fixation of the bed to the undercarriage.

4. Make the bed free from the connection plate on the mechanism.

5. Let the mechanism lower till the ambulance position is reached (see figure 5.7(b)).

6. Enough space for taking x-rays is present under the bed.

To make these actions safe, removing the fixation can only be done when the bed is connected to
the hooks and the rods. For example, the actuators can only be operated when the fixation of the
bed is intact or when both hooks and rods are connected to the bed.
The rods can be fixed to the undercarriage, rotating on one end and fixed into a simple clamp at
the other side. The rods can be rotated upright to support the bed.
5.3.2 Options for fixation of the bed on the connection plate

Two options for fixation of the bed on the connection plate can be seen:

**loading in x-direction** The bed is laid upon the connection plate and moved in x-direction. The bed slides over the connection plate and slides into the fixation.

**Loading in z-direction** The bed is positioned on the connection plate and fixated with clamps, screws or strips.

For sliding in driving direction, a rail or a rim is made under the bed in the fibre construction. (see C in figure 5.8(b)).

The rim under the bed encloses the connection plate at three sides. When these rims are made in a trapezium form, sliding over a small distance can make the bed free from the connection plate (see figure 5.8(a)). The connection plate can be 400 \( \text{mm} \) long. When the rim is 5 \( \text{mm} \) wide, a translation of 25 \( \text{mm} \) is enough to free the bed. When the hook allows a translation of 25 \( \text{mm} \), this option can be used. A round form of the edges of the connection plate (B) is needed in order to prevent cutting the bed with the connection plate when sliding.

![Figure 5.8 - Bed loaded in x-direction](image)

An option for "loading in z-direction" can be found in figure 5.9. A squared block is made under the bed. This block can be positioned in a hole in the connection plate. A large shear surface is created in this way. Fixation in the z-direction must be done apart, for example with a hook, strips, or a pin. Furthermore, the hole required in the connection plate weakens the connection plate.

![Figure 5.9 - Bed loaded in z-direction](image)
5.4 Final design

A top view of the bed can be seen in figure [5.10], a side view and cross-section in figure [5.11]. The bed can be 1850 mm long. In this case, the bed stays above the upper plate of the box in anti-trendelenburg position and in working position, the bed stays above the undercarriage.

On the head end of the bed, a push bar (A) is made. A tube with an outer diameter of 40 mm and inner diameter of 30 mm is used. The tube is fixed at both ends. The push bar is made of epoxy fibre composite, so $E = 2.5 \cdot 10^4 \text{ N/mm}^2$, the bending length is about 215 mm.

\[ f = \frac{F l^3}{3 E I} = \frac{500 \cdot 215^3}{3 \cdot 25 \cdot 10^4 \cdot \frac{\pi (40^4 - 30^4)}{64}} = 0.08 \text{ mm} \] (5.1)

Only 0.08 mm deflection is present when 50 kg is lifted at this end of the bed.

Under the matrass, canvas bags (C) can be made for storage of intubation tubes. These are stored in sachets of 100x300 mm. This bag fits between the connection plates and before beam 1 of the mechanism. It can be fixed to the bed using hooks on the bed and rings in the bag or with press-studs.

Four hand grips (B) are made in both sides of the bed. The handgrips are 100 mm wide and 40 mm high.

Slits for fixation of the matrass (E) are divided over the length and width of the bed, but not next to the connection plate. This will prevent sliding against the strips when fixating the bed. Because the slits and hand grips weaken the bed, the rim of the bed will be completely filled with epoxy fiber composite. The part of the bed where the connection plate is fixed is completely filled with epoxy fiber composite, too.

In the corner of the bed, besides the head of the patient, a connection board is made. The filter of the Servo 300 can be fixed to this board, so only the part of the tube from the board to the patient must be renewed. Other tubes can have a connection here, or are fixed to the bed, so the tubes will not pull on the patient when the bed is moved.
Figure 5.10 - Top view of the bed

bed bovenaanzicht (schaal 1:10)
Figure 5.11 - Side view and cross-section of the bed

bed zijaanzicht (schaal 1:10)  

BB (schaal 1:5)

doorsnede AA (schaal 1:10)
Chapter 6

Lay-out of apparatus

Personnel of the MICU can only take intensive care for the patient when they can make use of vital sign monitoring, ventilator, perfusion pumps, suction unit and defibrillator. When the apparatus in the MICU corresponds with that on the intensive care department, the personnel knows the apparatus and the apparatus on the MICU is exchangeable with that of the intensive care department. But, as can be seen in section 6.2, these apparatus are not made to build in or to be transported. Imagine the manufacturers of medical equipment would come together and develop an apparatus for all these functions with only one electrical connection, one battery and one display, a rather compact and easy to transport apparatus would be found to use in intensive care transport. Because such apparatus is not available, we will transport all these different apparatus in the best way possible. First, some principles to do so will be explained, in section 6.2 we will take a look at the equipment that is desired in the MICU and where it could be placed. In section 6.3, the final lay-out is explained.

6.1 Principles for placement of apparatus

In order to find an optimal place for each apparatus in the MICU, some principles will be used.

Each apparatus is placed in the undercarriage. Placing the apparatus in the undercarriage will make a stable construction because of the low centre of gravity. No equipment is fixed on the bed, so the patient can be reached from all sides. This is very important for moving the patient from the hospital bed to the bed on the MICU.

Apparatus placed under sight angle. In order to keep the apparatus in sight although placed in the undercarriage, the right angle must be chosen and each apparatus is placed so that displays or monitors can be seen from sitting position next to the MICU.

Concentration of mass. In order to create a stable and manoeuvrable MICU, the apparatus with the highest density must be placed as low and as nearest to the middle of the undercarriage as possible.

Before applying these principles on the lay-out, we will take a look at all the different apparatus and how they could be placed in the MICU.
6.2 Apparatus to be used in the MICU

6.2.1 Overview

Every Intensive Care Transport Team has its own requests for the equipment on the MICU. In table 6.2.1, the equipment of the transport teams that informed us about their requests are listed with their properties. The dimensions represent the rectangular box where the apparatus fits in (except for the gas cylinders).

<table>
<thead>
<tr>
<th>Description</th>
<th>WxBxH mm x mm x mm</th>
<th>weight kg</th>
<th>density kg/m³</th>
<th>power W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Servo 300A patient unit</td>
<td>242 x 250 x 370</td>
<td>18</td>
<td>800</td>
<td></td>
</tr>
<tr>
<td>Servo 300A control unit</td>
<td>440 x 330 x 150</td>
<td>6</td>
<td>275</td>
<td></td>
</tr>
<tr>
<td>Servo 300 patient unit</td>
<td>242 x 240 x 370</td>
<td>20</td>
<td>930</td>
<td></td>
</tr>
<tr>
<td>Servo 300 control unit</td>
<td>431 x 325 x 150</td>
<td>6</td>
<td>290</td>
<td></td>
</tr>
<tr>
<td>Servo 300 battery</td>
<td>415 x 85 x 330</td>
<td>18</td>
<td>1550</td>
<td></td>
</tr>
<tr>
<td>EvitaXL patient unit</td>
<td>340 x 425 x 295</td>
<td>23</td>
<td>930</td>
<td></td>
</tr>
<tr>
<td>Evita XL control unit</td>
<td>415 x 240 x 100</td>
<td>6</td>
<td>290</td>
<td></td>
</tr>
<tr>
<td>Laerdal premier suction unit</td>
<td>330 x 230 x 130</td>
<td>3,6</td>
<td>365</td>
<td></td>
</tr>
<tr>
<td>Philips M3046A monitor module rack</td>
<td>280 x 320 x 250</td>
<td>7,7</td>
<td>345</td>
<td>150</td>
</tr>
<tr>
<td>Philips M3046 monitor measurement server</td>
<td>137 x 329 x 130</td>
<td>2</td>
<td>340</td>
<td></td>
</tr>
<tr>
<td>Asena perfusion pump</td>
<td>310 x 117 x 140</td>
<td>2,5</td>
<td>500</td>
<td>20</td>
</tr>
<tr>
<td>Braun perfusion pump</td>
<td>360 x 120 x 200</td>
<td>3,4</td>
<td>395</td>
<td></td>
</tr>
<tr>
<td>air/oxygen cylinder 10 litre</td>
<td>960 x 150 diameter</td>
<td>17</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Lifepak 12 defibrillator</td>
<td>250 x 230 x 210</td>
<td>7</td>
<td>580</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.1 - Desired apparatus on the MICU

During the project, some hospitals changed the original plan to have four perfusion pumps on the MICU into six or even eight. In the final lay-out, four perfusion pumps are build in, in a way that answers the principles for a safe MICU, but in section 6.2.5, the placement of more than four perfusion pumps will also be discussed.

6.2.2 Gas cylinders

In order to respire the patient for 2 hours, 1800 liter of oxygen and air (15 liter/min) will be needed on the MICU [1]. Carrying 10 liter of gas at a pressure of 200 bar (which makes 2000 liter at atmospheric pressure) can be done in three ways: five bottles of 2 liter, 2 bottles of 5 liter or 1 bottle of 10 liter. The boiler formula yields:

\[ \sigma_t = p \cdot \frac{d}{2t} \quad (6.1) \]

and the thickness of the cylinder can now be derived:

\[ t = \frac{p}{2\sigma_t} \cdot d \quad (6.2) \]

So the volume of steel or aluminium of a cylinder wall is proportional with its diameter, but the volume of gas in the cylinder \( V = \frac{1}{4} \pi d^2 \) is quadratic with the diameter. Two ten liter bottles is the lightest option and can be found in table 6.2.1.
The gas cylinders are relatively large and of high density. The cylinders are closed after every trip, so the valve must be reachable. Furthermore, cylinders have to be changed once in a while and manoeuvring with a cylinder of almost 20 kg is not very easy. Therefore, the position of the gas cylinders in the MICU is very important and a good way to load the cylinders is necessary. Because of the length of the 10 liter gas cylinders, they cannot lay in the y-direction of the MICU. Figure 6.1 shows three basic options for the position of the gas cylinders.

![Figure 6.1 - Three basic options for loading the gas cylinders](image)

In figure 6.1(a), the gas cylinders are laid between the wheel houses, on the bottom of the MICU. Furthermore, only a small opening in the back plate of the MICU is necessary to load the MICU. The valves can easily be reached. In order to enable loading of the cylinders, the cylinders are laid in a tray. This tray could be made as a handtruck made from tubes or a foam tray. Slider strips or wheels are fixed under the tray. The end of the tray lands on an edge or with a pin in a hole, so the tray can be rotated around that point and lifted upright. It may even be possible to fix it to the console to prevent falling. An optimal position for working on the valves of the cylinders is reached.

Another option is loading the gas cylinders through a hole in the left wall (D) of the MICU. In figure 6.1(b), a part of a cross-section of the box in y-direction can be seen. In order to load the cylinders in this position, the cylinders can be fixed on the hatch (F). Closing the hatch will also load the cylinder. The second cylinder must be loaded with its own hatch, or the two cylinders are on the same hatch, which makes opening and closing the hatch heavy. The valves can only be reached when unloading the cylinders.

A third option for loading the gas cylinders in the MICU is can be seen in figure 6.1(c). The cylinder is loaded as a bullet in a gun, so the hole in the left wall of the MICU can be smaller than length x diameter of the cylinder.

The position of the cylinders between the wheel houses is the best position.

- The smallest opening to load the cylinders is used
- The valves of the cylinder can easily be reached and the cylinders can be unloaded easily.
- lowest position possible.
6.2.3 Batteries

Because the battery in the Servo 300 has not enough capacity to fulfill the 2 hours stand alone time, a separate backup battery can be delivered by its manufacturer. In figure 6.2, the Servo battery pack can be seen. When opening the box, four batteries can be found, a PCB and a transformer. The cables are long, so another layout of the batteries can be made without braking the existing connections. A control light burns when the battery is charging, which must be visible. The batteries in the Servo battery pack are taken out of the box and mounted apart from each other and upright, so the heat emission is better. A possible set-up can be seen in figure 6.2(b). The MICU of the VU Hospital (Amsterdam) uses a self build battery pack, that is very compact. A separate charger is necessary in that case, which can be seen in figure 6.2(c). Such a compact battery pack may also be used to feed non-medical features on the MICU such as the drive of the mechanism.

![Figure 6.2 - Batterypack](image)

6.2.4 Ventilation

A ventilator is necessary on the MICU in order to give artificial ventilation. The EvitaXL (Dräger, Lübeck, Germany) and the Servo 300 (Maquet, Solna, Sweden) ventilator consist of two units: a patient unit where the respiratory flow is produced and a control unit with which the ventilator is operated. These two units can be placed apart from each other. The ventilation unit must be operated during transport and must therefore be visible and reachable. A place at the head of the MICU would be desired. The length of the tube may not be too long, especially for children. In that case, the volume of the lungs is relatively small with respect to the volume in the tubes. A smaller diameter of the tubes will result in a bigger pressure reduction over the tube, $\Delta p \sim D^5$ [11]. The patient unit has inlets for air and pure oxygen and in- and outlets for the respirated air. A filter is used to keep the inside of the patient unit clean. This filter can also be placed on the connection board, so the tube between the connection board and the patient unit does not need changing every time the ventilator is used. The Oxylog ventilator is the only apparatus that is especially made for transport. This is only one small and compact unit and can be placed within the volume of the other ventilators. Therefore, this ventilator is not taken into account. The ventilation unit has to be connected to the gas circuit and to the electrical connection, both 220 V (for use in the hospital) and to the backup battery. The connections for air and oxygen are very unpractical. They reach a couple of centimeters outside the box. When building in these apparatus, these connections must be taken into account. A photo is taken from the control unit and the patient unit of the Servo ventilator and can be seen in figure 6.3. Figure 6.4 shows the EvitaXL ventilator. More detailed information about dimensions can be found in table 6.2. The existing connection between the control unit and the patient unit must not necessarily be kept, so every apparatus can be fixed apart in order to spread the collision and more positions are possible. The orientation of the patient unit with respect to the control unit can be changed, too. When the patient unit of the EvitaXL is rotated 90 degrees around the z-axis, the inlet of oxygen
and air is at the side of the cylinders and the connections to the ventilation tubes is on the side of the patients head. Because the unpractical placed connections and with use of squared connectors, the EvitaXL can be placed in a compartment that is 480 \text{mm} wide. Holes in the partition walls make it possible to mount the tubes on the EvitaXL and reach the flow transmitter. The control unit can be mounted in the front of the MICU in sight angle. Enough space is left to stick your hand into the MICU to reach the ventilation tubes. Because the Servo 300 control unit is 440 \text{mm} wide and the patient unit fits behind it, this respirator also fits in the compartment of 480 \text{mm} wide. The patient unit of the Servo must be placed in x-direction in order to fit.

The patient unit of the Servo can be placed between the wheel houses, but the control unit cannot be placed under the sight angle in that case. The EvitaXL patient unit is larger and does not fit between the wheel houses. Because the cylinders cannot be placed under or beside the ventilator, the ventilation compartment will, in x-direction, be situated between the bottom of the cylinders and the wheel houses.

The Servo-i (see figure 6.4(c)) is another type of respirator. Technical data of this respirator was only known very late in the project. Because the Servo-i patient unit is very high and may not be rotated according to the manufacturer, this part of equipment would only fit in the front compartment of the MICU, where more space is present, because the mechanism has already ended there. The Servo-i is narrow enough to fit between the wheel houses. When some critical valves in the apparatus can be rotated, the Servo-i will also fit in the same 480 \text{mm} wide compartment as the EvitaXL and the Servo 300.
6.2.5 Perfusion pump

Medication has to be administered by a perfusion pump. A hypodermic is clicked into the perfusion pump and squirted in a controllable way. This equipment must be controlled during transport so they are placed near sitting position in such a way that the displays are placed in the right angle to read out. The perfusion pumps can be exchanged for those on the Intensive Care and maybe, when stabilizing a patient, the perfusion pumps will be temporarily placed on the bed. Therefore, a simple fixation is needed. Infusion lines from the perfusion pumps to the patient may be tangled, so a way to guide the tubes would be desired. Figure 6.5 shows the Braun and Asena perfusion pumps.

![Perfusion pump](image)

**Figure 6.5 - Perfusion pump**

Figure 6.6 shows four schematic cross-sections of the undercarriage and four possible positions for the perfusion pumps. In figure 6.6(a), the perfusion pump is placed under the sight angle. The advantage of this position, is that the hypodermic points down, and air bubbles will stay in the hypodermic and not be injected in the vains. The Asena fits before the gas cylinders, but the Braun is deeper and does not fit in this position. The perfusion pumps can also be placed in x-direction, with the displays under the sight angle. This can be seen in figure 6.6(b). The Braun Perfusor will fit in this position, too. This position will cost a lot more space in x-direction and almost fills the front of the MICU, so there is no space left to store other things like medicine. When the upper perfusion pump is rotated, space can be created for a low but deep drawer, as can be seen in figure 6.6(c). The last option is pictured in figure 6.6(d), where two Asena perfusion pumps are fixed at the foot end of the MICU, before the mechanism. The Braun perfusion pump is too deep for this position. This position is hardly reachable during transport, but a combination of these options is also possible, for example 2 perfusion pumps under sight angle and 2 upright at the foot end of the MICU.

Figure 6.6 shows four options for placing the perfusion pumps.

![Four options for placing the perfusion pumps](image)

**Figure 6.6 - Four options for placing the perfusion pumps**

The four options as represented here are only suited for four (Asena) perfusion pumps. Some hospitals would rather have six or eight perfusion pumps. In this paragraph, some options will be presented for the transport of extra perfusion pumps, but this will not be taken into account for the final lay-out of the MICU.

**Another place in the undercarriage** Some of the hospitals do not need a suction unit or defibrillator on the MICU, so more space will be present to build in extra perfusion pumps. And in the future, it would be possible to have a brancard or MICU in the middle of the
ambulance floor with chairs on both sides. In that case, the back wall of the undercarriage can also be used for perfusion pumps.

**On a rail besides the bed** Mounting a rail besides the bed where the perfusion pumps are thread up is another option. The fixation of the perfusion pumps is not suitable to survive a 20 g collision. Therefore a new back of the pumps could be made from hard fiber material or aluminium with a crash worthy fixation.

**Integrated in the bed** Another possibility is making compartments in the bed, so the displays point upright.

These last options make the bed no longer suitable for rontgen photos and CT scanner. Furthermore, the center of gravity of the MICU is higher and the perfusion pumps must be carried by the mechanism. So the force on the perfusion pumps must leaded through the mechanism, through the undercarriage towards the fixation on the ambulance instead of directly via the box to the fixation. Another problem of mounting the perfusion pumps on the bed is the fact that they prevent sight on the other apparatus from sitting position (see figure 6.2.5)

![Figure 6.7 - Perfusion pumps prevent free sight on apparatus from sitting position](image)

### 6.2.6 Suction unit

A suction unit is used to suck fluids from the bronchial tubes and the mouth, and can also be used as a vacuum pump for the vacuum matras. The main parts of the suction unit are a pump, a battery and a pot to collect the fluids. The pot must be held upright. The 220V-connector puts out 55 mm. A photo of the Laerdal suction unit and a CAD model can be found in figure 6.8. Placement as in figure 6.9(a) can only be done in the front compartment of the MICU and enough space must be present between the wall units in the ambulance and the suction unit in order to

![Figure 6.8 - Laerdal Suction Unit](image)
operate it during transport. Placing at the other side is a better idea and can be done along the whole length of the MICU, because it fits before the mechanism and besides the gas cylinders. The suction unit is not the most operated equipment during transport and it is not necessary to have optimal sight on it. Switching on and off is enough. If the suction unit is placed at the foot end of the MICU, a switch must be placed at the front. In figure 6.9(c), the suction unit is placed in the front compartment. It can easily be reached in this position and this position leaves enough space for other equipment as the module rack or drawers with medicine and equipment.

6.2.7 Monitor

The monitor displays heart rate and ECG, transcutane oxygen saturation, respiration curve and frequency, non invasive blood pressure (measured with a band) and invasive blood pressure (measured in the artery with an infusion needle) and end-tidal CO$_2$-level. The monitor should be placed in such a way that both persons (the one at the head of the patient and the one besides the patient) can read the monitor. This can also be reached by adding an extra display to the monitor, which is possible with the M3046 monitor (see figure 6.10(c)). With the newest monitors, this can also be a bluetooth display, which is mounted in the ambulance. Although these advantages, AZM chooses the M3046A monitor, because the modules belonging to this monitor correspond with the modules used at the IC beds, so the alarm settings can be transferred to the Intensive Care in an easy way. These modules are clicked into a rack, that can be mounted on the back of the monitor or is mounted apart in the MICU and connected with a cable. This is possible for both monitors.

Three options for placement of the monitor can be seen in figure 6.11. In figure 6.11(a), the monitor is placed under the sight angle. This can be done along the length of the undercarriage, even above the wheel houses, but we want to place the monitor at the head end of the MICU, besides a blind wall at the front of the MICU, which is a good way to fix the monitor. Another option (see figure 6.11(b)) is placing the monitor in the driving direction, but fixation in this direction is more difficult. The monitor is now better visible for the man or woman sitting at the head end of the MICU, but the bed prevents free sight on the monitor in contrary to the first option. In figures 6.11(a) and 6.11(b), the M3046A monitor is shown, but the smaller M3046
6.2. APPARATUS TO BE USED IN THE MICU

6.2.8 Module rack

In order to be able to reach the modules during transport, the module rack is fixated apart and not at the back of the monitor. Of course, the connection with the monitor must be made, but a rather long cable can be delivered. This part of equipment could also be placed under the sight angle, but reaching the modules during transport is enough. Other apparatus is more frequently used. In figures 6.11(b) and 6.11(c), the module rack is placed upright. A lot of space for other equipment is left, but the top of the module rack will reach higher than the other equipment. This is possible in the front of the MICU. In figure 6.12(c), the module rack is placed in the front compartment and is rotated under sight angle. The bed prevents free sight on it, but the modules are reachable. Furthermore, there is enough space left for a drawer under the module rack and other equipment placed after the module rack could be reached, too.

Figure 6.11 - Three options for placement of monitor

Figure 6.12 - Three options for placement of module rack
6.2.9 Defibrillator

A defibrillator is used for electrical shocks in dysrhythmia of the heart.

![Defibrillator](image1)

![Defibrillator](image2)

Figure 6.13 - Lifepak 20 defibrillator

The defibrillator does not need a prominent place in the MICU for children, although it should be in adult transport. When necessary, the defibrillator is taken out of its compartment and placed on the bed. The defibrillator can be stored just in front of the mechanism in the compartment at the foot end.

6.2.10 Medication and disposables

A lot of medication and disposables are needed on the MICU. They will be stored in several bins and compartments in the undercarriage and under the bed. A complete list of equipment can be found in appendix B.
6.3 Final lay-out

In order to find an optimal lay-out for the apparatus on the MICU, mock-up versions of all apparatus were made in foam (see figure 6.3 for some examples). These blocks can be fitted in most varying positions in the mock-up of the undercarriage. This mock-up is a steel tray with the wheel houses in it and the wheels mounted in the mock-up. This mock-up of the undercarriage can be seen in figure 6.3. A couple of days shifting equipment and positioning the apparatus in all possible orientations made the optimal lay-out clear. In this paragraph, we will explain the final lay-out.

![Mock-up of undercarriage and apparatus](image)

Figure 6.14 - Mock-up of undercarriage and apparatus

![Compartments of box](image)

Figure 6.15 - Compartments of box

Because the gas cylinders and respirator do not fit besides each other, and because the respirator cannot be placed between the wheel houses, compartment 2 in figure 6.15 will be the ventilation compartment. This compartment is 480 mm wide. The front compartment (compartment 1) is the place for the monitor, the suction unit and the module rack. The monitor is mounted under sight angle, because this position can be used for both monitors. The suction unit is placed against the partition wall, because it is reachable from sitting position at the head end of the MICU. The modulerack is placed horizontal with the modules pointing to the doctor or nurse at the head end, in front of the suction unit. The suction unit can be reached over the module rack and under the module rack is space for other equipment, in a drawer or tray between the wheel houses. The gas cylinders are 960 mm long and will be placed between the wheel houses. The tunnel around the cylinders sticks through compartment 3, 4 and 5. This tunnel cannot be used to guide the forces from the back wheels to the front, because it is not that long. Rectangular tubes connect the wheel houses at the front with those at the back. Behind this tunnel, in compartment 3 is space for the batteries. These are now placed in the middle of the MICU and on the bottom of the undercarriage. Compartment 3 can also contain the perfusion pumps, which will be placed under the sight angle and slightly rotated around their longitudinal axis, so the displays point to
the sitting position of the doctor or nurse. Only the Asena perfusion pumps fit in this position, but the advantages as mentioned in section 6.2.5 are considered so valuable, that this decision is made. Four perfusion pumps fill the front of compartment 3 and in compartment 4 is space for drawers, trays or roly-kit-like storage area. The drawers must be opened during transport. In compartment 5, the defibrillator is put away before the mechanism and hydraulics that fill the rest of compartment 5. At the other side of the mechanism there’s space for long material like drip bars. Storage area is also present under the bed, before and at the ends of the mechanism. This area can also be used for storage of endotracheal tubes (front) and intra-venous cannulas (back). This will be explained in chapter 5.

The hydraulic pump can be placed in compartment 3, behind the perfusion pumps.

One connection for connection to the gas network of the hospital or the ambulance and one for connection to the electrical circuit must be made on the MICU. The gas tubes could be a separate tube, with a male and female connector. The ends of the tube can now be connected, so the tube will stay clean. For the connection to the electrical circuit, a roll automaton can be used.

The center of mass of the equipment can be calculated with ALGOR. The center of mass is situated 255 mm above the floor, 310 mm from the side with the equipment and 1030 mm from the back end of the MICU. A low center of mass, situated about the middle of the undercarriage is realized.
Chapter 7

Fixation of the MICU in the ambulance

During transport the MICU has to be fixated in the ambulance in all directions. This fixation must be crashworthy till 20 $g$. A rigid fixation transmits the forces acting on the ambulance directly to the MICU. When kinetic energy is absorbed over a long way, the forces that act on the MICU will be lower.

The forces that act in a collision are subject of section 7.1. Absorbing kinetic energy in plastic deformation is explained in section 7.2. An experiment is described and performed in section 7.3. The final design of the fixation of the MICU in the ambulance is described in section 7.4.

7.1 Forces acting on the MICU

In figure 7.1 a schematic drawing of a crash test can be seen. The ambulance crashes on the concrete block at the right side. The kinetic energy of the ambulance and all its contents must be absorbed in order to slow it down.

![Figure 7.1 - Forces and displacements in a crash](image)

The MICU must be crashworthy till 20 $g$. A 20 $g$ deceleration acting on an ambulance of 2000 kg results in a force of 400 kN acting on the ambulance. The force on the ambulance during the crash is assumed to be constant. When the kinetic energy of the ambulance is absorbed in 600 mm deformation, the kinetic energy was

$$E_{\text{kin}} = F \cdot s = 400 \text{ kN} \cdot 600 \text{ mm} = 240 \text{ kJ}$$

(7.1)
This amount of kinetic energy is reached at a speed of

\[ E_{\text{kin}} = \frac{1}{2}mv^2 = 240 \text{ kJ} \rightarrow v = \sqrt{\frac{240 \text{ kJ}}{\frac{1}{2} 2000 \text{ kg}}} = 15.5 \text{ m/s} = 56 \text{ km/h} \]  

(7.2)

The MICU and the patient can be given a relative displacement with respect to the ambulance (see figure 7.1). The MICU can travel 100 mm in the ambulance in order to absorb more energy. The equipment in the MICU can travel another 10 mm and the patient may even travel another 100 mm with respect to the MICU. The weight of the MICU including the patient and equipment is assumed to be 300 kg. The force on the MICU in a crash is

\[ F = m \cdot a = 300 \text{ kg} \cdot 20 \cdot 10 \text{ m/s}^2 = 60 \text{ kN} \]

Because most crashes occur in driving direction, energy absorption is done in this direction. Energy absorption in plastic deformation is the subject of the next paragraph. The design of a fixation that can handle a reaction force of 60 kN during 100 mm travel in x-direction (thus absorbing 6 kJ of kinetic energy) and forces in y and z-direction is the subject of paragraph 7.4.

### 7.2 Energy absorption in plastic deformation

Energy can be absorbed in plastic deformation, which can occur in tension, shear and bending. For plastic deformation, stress in linear elastic - ideally plastic material equals the yield stress. The energy absorbed in a certain volume of this material can be defined as

\[ E_{\text{abs}} = \sigma_y \int_V |\epsilon_{\text{pl}}|dV \]  

(7.3)

where \( \sigma_y \) is the yield stress of the material and \( \epsilon_{\text{pl}} \) is the plastic strain.

In case of tension, the volume of material to absorb 6 kJ of energy can be calculated. In case of tension, the relative strain \( \epsilon \) is assumed to be constant over the whole volume. For steel, \( \sigma_y = 340 \text{ N/mm}^2 \). 25% plastic strain is assumed. Elastic strain is only about 0.2% and is therefore neglected.

\[ E_{\text{abs}} = \sigma_y \int_V |\epsilon_{\text{pl}}|dV = \sigma_y V|\epsilon_{\text{pl}}| \rightarrow V = \frac{E_{\text{abs}}}{\sigma_y|\epsilon_{\text{pl}}|} = \frac{6000 \text{ J}}{340 \text{ N/mm}^2 \cdot 0.25} = 70 \cdot 10^3 \text{ mm}^3 \]  

(7.4)

For example four bars with diameter 7,5 mm and a length of 400 mm are enough to absorb 6 kJ of kinetic energy. The work needed to deform the bars can be calculated. The force needed to reach the yield stress in the material is

\[ F = \sigma_y A = 340 \text{ N/mm}^2 \cdot 4 \cdot \frac{1}{4} \pi (7.5)^2 = 60 \text{ kN} \]

This force is applied during the travel \( s \) which equals the elongation of the bars \( \epsilon l = 0.25 \cdot 400 \text{ mm} = 100 \text{ mm} \). The work equals

\[ F \cdot s = 60 \text{ kN} \cdot 100 \text{ mm} = 6 \text{ kJ} \]

Plastic deformation in shear can better be used to absorb energy, because strain can be larger than in tension. Where 30% strain is very much for tension, strain can be till 100% in shear. In practice, it is very hard to deform all material in shear [12]. Let us assume half of the material will be plastically deformed, than only half of the amount of material is needed as it was for tension. Bending can be used to absorb energy during a relatively long travel when a traveling deformation front is created in a strip or plate and most of the material is deformed plastically. For example, when a piece of paper is crushed, the material is only plastically deformed in the sharp folds. The strip is bent over a radius that equals its thickness, plastic strain at the outer fiber is relatively large and a lot of energy can be absorbed. When assuming 50% and 25% strain at the outer fibers, a mean strain of 37.5% is realized.
In figure 7.2(a), a possible setup for energy absorption in bending of a strip can be seen. A strip is bent in a U-form and than the two legs of the U are bent back over 180 degrees with radius R1. The hammer (A), rounded with the same radius as used in the first bending, lies between two strips. These strips are fixed in a clamp (C) which makes sure the bending radius remains the same during deformation. The MICU is mounted on a couple of hammers A. When a collision occurs, the MICU will move in x-direction. When hammer A moves in x-direction, the strip at the right side is deformed. This can be seen when we zoom in on the strip, in figure 7.2(b). When hammer (A) moves in x-direction, the undeformed material as in point 1 is bent (as the material in point 2). When moving further, the material is bent back as the material in point 3. So, every deformed part of the strip is twice plastically deformed!

This setup makes it easy to provide energy absorption in positive (using the right strip) and negative x-direction (using the left strip in figure 7.2(a)) in a compact way. The amount of energy that can be absorbed using these sort of strips can be calculated using (7.3). This can be seen in appendix G. The equation can be rewritten in terms of the force acting on the strip during deformation.

\[ F = 2\sigma_y b \left\{ \frac{1}{2} T^2 - kT^2 + k^2 T^2}{R + kT} + \epsilon_{el,max}^2(R + kT) - \epsilon_{el,max} T \right\} \]  

(7.5)

The maximum strain at the outer fibres is determined by the relative position of the neutral axis \( k \) and the ratio between the thickness of the strip \( T \) and the bending radius \( R \). Special materials may reach a strain of 60%, but 50% strain can be reached using normal carbon steel. When \( R = T \) and \( k = 0.33 \), 50% and \(-25\%\) strain at the outer fibres is realised. Variation of the thickness and the width of the strip make it possible to dimension energy absorbing fixtures. The maximum elastic strain is assumed to be \( \epsilon_{el,max} = 0.1\% \).

The force needed to deform the strip for different values of the yield stress \( \sigma_y \) can be calculated as a function of the parameters in figure 7.4. This relation is shown in figure 7.3. The values for \( T = R \) at the grid lines equal commercially available plate thicknesses.

The force of 60 kN acting on the MICU can be divided over 4 fixtures. Deformation of 3 mm strip requires a force of 425 N/mm as can be found in figure 7.3 for \( \sigma_y = 340 \, N/mm^2 \). This strip must be \( \frac{\frac{150000 \, N}{425 \, N/mm}}{35 \, mm} = 35 \, mm \) wide.
Figure 7.3 - Force on energy absorbing strip per mm width

Figure 7.4 - Parameters for dimensioning of strip
7.3 Testing of energy absorption strips

In the preceding paragraph, a lot of assumptions have been made. Except for the assumptions on the deformation of the ambulance and the constant deceleration during the collision, assumptions have been made on the yield stress, position of the neutral axis and maximum elastic strain. The calculation is based on constant parameters and linear elastic - ideally plastic material behavior. A relatively simple experiment to find out if such a strip could absorb 1.5 kJ over a length of 100 mm is a push test. The force $F$ (see figure 7.4) is made and measured with a tension test machine during deformation. Alternatives for this test would be a droptest. The potential energy of a mass of 150 kg on a height of 1 m above the strip equals 1.5 kJ: $E_{pot} = m \cdot g \cdot h = 150 \cdot 10 \cdot 1 = 1.5 \text{ kJ}$. A guidance for this relative heavy weight must be present to do such a test.

For simplicity, the push test is chosen. Five strips (5 in figure 7.5(b)) are produced and mounted in the block in order to be tested. This block makes sure the distance between the plunger (2) and the walls (4) are constant and therefore the bending radius. The strip (5) leans on the bottom of the block (6). The strip is mounted to the sidewalls of the block, however it leans on the bottom of the block when the strip is loaded. The whole block is mounted on a table of the tensile testing machine with help of some clamps that can grab in the slot that is milled in the side wall. Buckling of the strip will not occur. The pushing force acts besides the strip and therefore the direction of buckling is determined. The side wall of the strip prevents this. The block can also be used as a compression mould for deforming the strip. Therefore, the edges of the sidewalls are rounded with a radius cutter.

The block and plunger are made in the workshop of the group Constructions and Mechanisms at the TU/e. In figure 7.5, the drawing of the construction and a picture can be seen.

![Figure 7.5 - Experimental setup for testing of energy absorption strips](image)

The speed during the test is presented in table 7.1.

A tensile test is performed in order to characterize the material behavior of the strips. Results of this test can be found in section G.1. The force needed to deform this 32 mm wide strip using the yield stress as determined in the tensile test is 12.1 kN.

The data from the test is plotted in figure 7.6. After the elastic deformation (3 till 3.2 mm), the
CHAPTER 7. FIXATION OF THE MICU IN THE AMBULANCE

<table>
<thead>
<tr>
<th>number</th>
<th>deformation speed</th>
<th>preload</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10 mm/min</td>
<td>50 N</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>10 mm/min</td>
<td>50 N</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>20 mm/min</td>
<td>50 N</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>10 mm/min</td>
<td>50 N</td>
<td>stress-relieve by annealing (6 h, 600 °C)</td>
</tr>
<tr>
<td>5</td>
<td>40 mm/min</td>
<td>50 N</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.1 - Test conditions

![Figure 7.6 - Data from compression test](image)

part of the strip that was deformed in producing the strip is deformed (till $s$ is about 40 mm). The last part of the figure shows an almost constant force. Although statistic certainty cannot be reached from a test with 5 strips, we may conclude a force of about 14.5 kN is needed to deform the strip.

This test proves dimensioning the strips for energy absorbing fixtures with the data in figure 7.3 can be done.
7.4 Fixation of the MICU

Fixation and drive of objects must be applied as close to the center of gravity as possible in order to minimize forces and moments. The point where the MICU is fixated must be stiff and strong enough for the forces acting on the fixation. Simple actions for fixation raise user-friendliness and make the fixation more reliable. Furthermore, the MICU must be loaded into the ambulance. Fixation of a normal stretcher must be possible in the same ambulance.

7.4.1 Connection of the MICU to the energy absorbing fixtures

Two basic options for a connection of the MICU to the energy absorbing fixtures are explained in this section.

The first option is the elongated back plate of the wheel house. This plate is situated right behind the wheels and does not influence the play between bottom of the MICU and the ground. Forces in z- and x-direction act in the plane of the plate, so transmission of the forces to the MICU can be done very well. The distance between the fixtures in x-direction is very large, but in y-direction only 330 mm.

A pin mounted in the corner of the wheel houses or even further from each other in y-direction is the second option. This pin is also stiff and strong in y-direction.
We will take a look at some alternatives to connect the MICU to fixtures using these options.

Figure 7.7 - Four options for fixation of MICU with plate

Figure 7.7(a) shows the plate on the wheel house (A). The energy absorbing strips (B) are mounted in a rectangular tube (C). A slit is milled in the side of the tube. The left tube contains two slits. A pin (D) is pushed through the left hammer (E), through the plate on the wheel house (A) and into the right hammer. The MICU must be driven between the fixtures. When all four plates are between the fixtures, the pins can be pushed in the holes of all plates. The pin searches the hole because of the chamfer at the end. Pushing the pin into the relatively long holes may be a problem. Furthermore, a difference between the energy absorbing strips in the fixtures results in different forces and therefore in a rotation of the pin and bending of the plates (A).

In figure 7.7(b), two plates (F) are fixed in the hammer (E). One plate (A) is now connected to one energy absorbing fixture.

A lock as in figure 7.7(c) can be used to catch a tube. This tube could be a connection between two fixtures as the left one in figure 7.7(a). When loading the MICU, the lock is open, but when the tube (I) comes further into the hole of the fixed part of the lock (G), the tube rotates the rotating part (H) that closes the hole.

A fourth option is inspired on the lock of safety belts. The plate (A) is driven into the U-formed plate (J) till the end. Than the lock (K) springs into the hole in the plate and fixates the plate. Fixation is done automatically, just as for the preceding option, and only action must be taken to release the MICU.
For fixation with the pin, several options can be found to fixate the MICU to the fixtures.

(a): Figure 7.8(a) shows a sort of keyhole. The pin (A) is pushed in the hole (B). A displacement in the hole (B) brings the pin in the position as in figure 7.8(a). Because the diameter of the pin is larger under the plate, movement in z-direction is prevented. A movement in z-direction and in plane is necessary to fixate the MICU.

(b): The pin can also be fixed to the block using a clamp (C) (see figure 7.8(b)). This clamp closes around the pin, in a groove in the pin. The shear strength of such a spring steel clamp is very high, so a strong fixation can be realised. Pushing the pin into a hole is necessary for this option.

(c): Figure 7.8(c) shows an option where the movement of the pin down to the fixture is used to fixate the pin in z-direction. The pin is mounted in a tube in the MICU (D). Pushing the plunger (I) downwards results in downward movement of the plunger (I) and the tube (F) which are connected to each other by a spring (G). When the tube reaches the bottom of the rectangular tube of the fixture, the plunger (I) can be pushed further. This results in pushing the balls (H) through the holes into the bore in the hammer (E) of the fixture. These balls prevent movement in z-direction of the pin. The pin transmits forces in the x-direction and y-direction to the middle of the hammer. The bore angle makes sure the balls slide back into the pin.

The pin fixates the MICU in x-, y- and z-direction, where the plate only fixates in x- and z-direction. The last option (see figure 7.8(c)) provides a simple mechanism to connect the MICU to the energy absorbing fixtures that makes loading of the MICU easy. Furthermore, the distance in y-direction between the pins can be larger than the distance between plates on the wheel houses. This minimizes the forces on the fixation.

The operation of the fixation is considered. The pin sliding into the hole in the hammer and pushing the balls outwards can be done with one movement.
(a): A knee-lever can be used to operate the pin. The open position is drawn with solid lines in figure 7.9(a). The midpoint of the mechanism (M) is moved along the dashed line c till the stop (B) is reached. The spring in the pin (see G in figure 7.8(c)) pushes the knee lever against the stop or to the actuation, which moves midpoint (M).

(b): A lever (D) as in figure 7.9(b) can also be used to operate the fixation. The built-in height of this mechanism is smaller. A pin (E) reaching out the MICU could be used to actuate the fixation when the MICU is loaded.

(a): The pin (A) (which is the same pin as (I) in figure 7.8(c)) must be kept in the down position to prevent rolling back of the balls. Therefore the mechanism must be bi-stable. The lever is drawn in upper (solid lines) and down position (dashed lines) in figure 7.10(a). Spring (F) pulls the lever against the push rod (E). Pushing the rod (E) results in a rotation of the lever (D). When rotating the lever over the neutral position (n on curve d) the spring (F) pulls on the other end of the turning point of the lever and pulls the lever against the stop (J).

(b): In figure 7.10(b) a spring (G) is used to push the pin to the open position. A beam (H) is mounted under the lever. The spring (I) pushes the beam against the lever. When the lever is rotated, the beam (H) is pushed down and jumps back against the lever when the lever has passed the beam. For releasing the MICU, the beam H is rotated downwards. The spring (G) pushes the lever (D) back to the open position. The pin will be operated by the bi-stable mechanism as in figure 7.10(a). Fewer parts are needed for this mechanism than for the option in figure 7.10(b).
When the fixation is in open position, the push rod (E) is outside the wall of the MICU. The push rod falls into a hole in the wall. Therefore, releasing cannot occur accidentally.

For dimensioning the fixation mechanism, forces in y- and z-direction must be known. These forces can be calculated using equilibrium of moment on the MICU as can be seen in figure 7.11(a) and 7.11(b). Therefore, the distance between the fixation points must be known and the height of the center of gravity. The fixation pins are situated between the wheel houses, as wide as possible between the wheels. $l_{b,x} = 1400 \text{ mm}$ and $l_{b,y} = 440 \text{ mm}$ is assumed. The height of the center of mass can be calculated. The centre of mass of the undercarriage is assumed to be somewhat above the middle of the undercarriage on $225 \text{ mm}$. The patient is flat on the bed and the centre of mass of the equipment was calculated in chapter 6. This is listed in table 7.2 and the overall center of mass is calculated.

<table>
<thead>
<tr>
<th>part</th>
<th>distance [mm]</th>
<th>mass [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>patient</td>
<td>800</td>
<td>100</td>
</tr>
<tr>
<td>equipment</td>
<td>155</td>
<td>120</td>
</tr>
<tr>
<td>undercarriage</td>
<td>225</td>
<td>80</td>
</tr>
<tr>
<td>combined</td>
<td>390</td>
<td>300</td>
</tr>
</tbody>
</table>

Table 7.2 - Center of mass of MICU

Forces on the fixtures in a crash in driving direction:

$$F_{z1} = F_{z2} = \frac{l_{cm}}{l_{b,x}} F_{crash,x} = \frac{390}{1400} 6 \text{ kN} = 1670 \text{ N}$$  \hspace{1cm} (7.6)

In a side impact, forces on the fixation can be calculated

$$F_{y3} = F_{y4} = \frac{l_{cm}}{l_{b,y}} F_{crash,x} = \frac{390}{440} 6 \text{ kN} = 5320 \text{ N}$$  \hspace{1cm} (7.7)

Because these forces are divided on two fixtures, the fixation must be able to resist $1.5 \text{ kN}$ in x-direction, $1.5 \text{ kN}$ in y-direction and $2.7 \text{ kN}$ in z-direction. The wall thickness of the pin is the same as the radius of the balls in the fixation. A pin with outer diameter $20 \text{ mm}$ and inner diameter of $14 \text{ mm}$ in combination with three $6 \text{ mm}$ balls is used. The shear stress in the pin yields:

$$\sigma_s = \frac{F}{A} = \frac{15000}{\frac{1}{4} \pi (D^2 - d^2)} = \frac{15000}{\frac{1}{4} \pi (20^2 - 14^2)} = 94 \text{ N/mm}^2$$  \hspace{1cm} (7.9)

In z-direction, shear in the balls is present as a result of a force in positive z-direction. This force could be maximal

$$F_{z,ball} = \sigma_{s,ball} A = 600 \text{ N/mm}^2 \cdot 3 \cdot \pi r^2 = 600 \text{ N/mm}^2 \cdot 3 \cdot \pi \cdot 3^2 = 50kN$$  \hspace{1cm} (7.10)

for three balls.
7.4.2 Energy absorbing fixtures

The energy absorbing fixtures are mounted in the ambulance. Mounting of the energy absorbers in the MICU would require space in the undercarriage that could be used for other equipment. Furthermore, the energy absorbers can now also be used when a normal stretcher is mounted in the ambulance. The aluminium tray that is mounted in ambulances can now be fixed on the fixation frame.

In figure 7.12, the fixation of the MICU can be seen. In order to load the MICU into the ambulance, the fixation fits between the wheels, but is as wide as possible to minimize the forces. The space between the side walls of the frame can be used to store some medical equipment. The rims of the frame (C) can be used to mount the frame to the chassis beams of the ambulance. The rounded form at the back end of the ambulance makes it easier to load the MICU (see figure 7.13). The energy absorbers are fixed in the corners of the fixation frame. Slits are milled in the frame to permit translation in x-direction. The wheels of the MICU are driven between two plates on the tailboard or the ambulance floor. The MICU is now set on its place within only one or two millimeters. This is enough to fixate the pin into the hammer of the energy absorbing fixture. The height of the frame must be 2 millimeter less than the space between the bottom of the MICU and the ambulance floor. This gap is small enough to fixate the MICU with the fixation pin and large enough to fit when the wheels are worn out after a few years of use.

The whole construction of the hammer and energy absorbing strips is mounted in a rectangular tube 60 x 40 x 3(G). Figure 7.14 shows a cross section, more views and cross-sections can be found in figure 7.15. The position of block (A) and the deformed form of strips B and C after a forward or backward crash is drawn with dashed lines. This tube is mounted in the frame. The length of the tube is 475 mm so it does not stick out of the frame before the MICU, the construction has an easy to handle size for production and is long enough to fit a hammer (A) in the tube that is longer than the slit in the tube. The thickness of the hammer is enough to fill the tube in...
z-direction. The corners of the hammer are rounded to make sure the hammer slides in the tube and does not get stuck in the wall. The form of the hole in the hammer makes it easy to find the hole with the fixation pin. Forces in x-direction are transmitted to the rectangular tube (G). The strips (B and C) are mounted to the wall of the rectangular tubes with rivets (K).

![Cross-section of energy absorbing fixture](image)

Figure 7.14 - Cross-section of energy absorbing fixture

When a crash has occurred, the strips must be changed. A hole in the side wall of the rectangular tube makes it able to see the hammer. When the spot behind this hole is marked, a displacement of the hammer can be recognized.

In chapter 3, a plunger lock was presented as an option to reduce wear of the wheels. Another possibility to unload the wheels when the MICU is not used and to prevent driving away when the MICU is still connected to the electrical circuit and gas supply of the hospital is a docking station. This could look like the frame in the ambulance as in figure 7.13, but can be made of, for example, wood, because the strength needed in a crash is not necessary for a docking station. The MICU is lifted a few millimeters in order to tilt the wheels free from the ground.

The tray for a normal stretcher can be connected to four energy absorbing fixtures that lay between the fixtures for the MICU. The strips in these fixtures can be adapted for the normal weight on the stretcher with help of figure 7.3. Because the center of mass of a normal stretcher is lower and is lighter than the MICU, fixtures can be somewhat closer to each other. The fixation mechanism (as in figure 7.8(c)) can be made on the tray and operated by hand.
Figure 7.15 - Design of fixture
Chapter 8

The undercarriage of the MICU

Now the positions of the equipment and the mechanism are known, the undercarriage can be designed. The global layout of the undercarriage is shown in a cross-section of the undercarriage (figure 8.1(a)). A 3D view is shown in figure 8.1(b). The gas cylinders almost fill the width between the wheel houses. The cylinders are laid in a tunnel between the wheel houses in which the tray with the gas cylinders is fixed. A rectangular tube between the wheel houses at the foot end and those at the head end connects the front with the back. This tube can also be used to guide cables and tubes of the equipment and for the operation of the wheels. A console is made on the undercarriage. A bent tube is attached to it in order to push the MICU. The control panel for operation of the wheels and the hydraulics for the mechanism is made on the console. A triangular tube is constructed at both sides of the MICU (see figure 8.1(b)). These tubes can be used to guide the cables and tubes to the control panel.

The mounting of the hydraulic cylinders and the mechanism is explained in section 8.1, the lay-out of the front compartment of the undercarriage in section 8.2. Finite element simulations are performed on the undercarriage to optimize the construction. By showing the process of optimization, the development of the undercarriage is explained (see section 8.3).
8.1 Mounting of mechanism and hydraulic cylinders

Figure 8.2(a) shows cross-section AA of figure 8.1(a). Cross-section BB of figure 8.2(a) can be seen in figure 8.2(b). The tunnel for the gas cylinders has a bigger opening than the height of the cylinders in order to be able to operate the valves on the cylinders. The upper plate of the tunnel is therefore mounted under an angle, that is determined by the space needed for the actuation of the mechanism. The forces acting on the bearings of the mechanism must be transmitted to the undercarriage. Two plates through the upper plate of the undercarriage to the bottom would fulfill this function. Because the bottom of the MICU cannot be reached without cutting the gas cylinders, these plates (A and B), are mounted to the top plate of the cylinder-tunnel (C).

The mechanism is mounted between the plates A and B. These plates correspond with the plates G in figure 4.25. At the right side, a hole is made in plate B and plate C is cut off in order to store defibrillator.

The hydraulic cylinders are mounted between the plates F. This form is needed to provide space for the cylinders and the trendelenburg actuation body. Plate G connects the plates F to each other and to the plates A.
8.2 Lay-out of compartment 1

Cross-section BB of figure 8.1(a) can be seen in figure 8.3(a). Cross-section AA of this figure can be seen in figure 8.3(b). The front compartment contains the suction unit, the monitor and the module rack. The module rack and the suction unit are loaded through a hatch in the left wall of the MICU. The monitor can be loaded through the hole in the right side wall under the sight angle.

Figure 8.3 - Cross-section of compartment 1 of undercarriage
8.3 Optimization of undercarriage using FE element simulations

With help of ALGOR, Finite element simulations of a crash and normal load are made. In a crash, a deceleration of $20 \, g$ is acting on the MICU. The equipment is slowed down by the undercarriage and forces of $F_{\text{app,c}} = m \cdot 20 \, g$ act on the partitions of the undercarriage. Because the equipment is mounted in foam blocks at the corners, there is no play between the equipment and the undercarriage, every piece of equipment can be fixed easily and deformation of the foam absorbs some energy in a crash. Because of the foam blocks, the forces act in the corners of the compartments. A schematic drawing of the load on the MICU in a crash can be seen in figure 8.4(a).

A force of $F_{\text{bed,c}} = m \cdot a = 200 \, kg \cdot 20 \cdot 10 \, m/s^2 = 40 \, kN$ acts on the axle, that is $25 \, mm$ away from the middle of the plate that fixates the mechanism (A in figure 8.2(a)). The moment acting on the undercarriage is taken into account. Because the distance between the two plates A and B (see figure 8.2(a)) is twice as big, the force on the outer plates B is only half of this force. (10 $kN$). The force on the two inner plates A is 30 $kN$.

![Diagram](a)

Figure 8.4 - Loads acting on the MICU in a crash and in normal situations

In normal situations, gravity is only $g$, acting in negative z-direction. All equipment rest in their compartment with a force $F_{\text{app,z}} = m \cdot g$. The mechanism is in the working position, so the forces acting on the MICU are $F_{\text{bed,n}} = F_d + F_c$. These forces are calculated in chapter 4. The force and the moment on the MICU is applied as a $F_{\text{bed,n}} = 9.2 \, kN$ in direction $[x, z] = [9, -1, 875]$ that acts on both plates A and a force of 3 $kN$ acting in opposite direction on the outer plates B. The actuation forces $F_{\text{act,h}} = 24 \, kN$ in negative x-direction and $F_{\text{act,t}} = 18 \, kN$ in positive z-direction act on the MICU in order to keep the bed in working position.

The simulation is started with plate thicknesses of 1,5 $mm$ for most plates. The gas cylinders and batteries are very heavy, so a plate thickness of 3 $mm$ is used at the end of these compartments. The plates of the mechanism (A,B,F) are 4 $mm$ thick.
When a crash simulation is performed, maximum stress is $270 \, N/mm^2$ (see figure 8.5(a)). Except exceeding the yield stress, buckling may also cause failure of the MICU. Therefore, the critical buckling load is computed. The load multiplier before buckling occurs is the outcome of the simulation. Furthermore, the buckling form can be seen in ALGOR. For the first crash simulation, the critical buckling load multiplier is 0.8. The top plate and back wall of the undercarriage will buckle in compartment 3 (see figure 8.5(b)).

In order to prevent buckling of the top plate, an omega-profile is welded to the plate, in line with the plates A and B (see figure 8.2(a)). A thin plate is enough, 0.35 mm steel plate is used in the calculation. Figure 8.6 shows cross-section CC of figure 8.1(a). The added profile is marked L. The other profiles will be explained in the rest of this section.
When omega profile L is added, the same plate buckles (see figure 8.7). The load multiplier is 1,3.

The weight of the undercarriage is now 96.5 kg. Because the stress in a crash is less than the yield stress, thinner plates can be used. The thickness of the bottom, top and side plates is reduced to 1 mm. The thickness of the plates of the compartment for the perfusion pumps is also reduced to 1 mm. The weight of the model is now 87 kg. Static stress and critical buckling load simulations are performed again. The result of the static stress simulation can be seen in figure 8.8.

Buckling occurs in the same way as in figure 8.7. The load multiplier is 0.5. The maximum stress is 320 $N/mm^2$ and can be found in the corner of the front compartment and in the partition 12. The corner of compartment 1 is stiffened by a small rim of 10 mm around the edges of the compartment. The partition between compartments 1 and 2 is stiffened by a plate just above the suction unit (see P in figure 8.3(b)). The finite element model is modified and static stress and critical buckling load simulations are performed. The stress in a 20 g crash is shown in figure 8.9.
8.3. OPTIMIZATION OF UNDERCARRIAGE USING FE ELEMENT SIMULATIONS

Buckling occurs in the bottom plate, in the cylinder compartment. This can be prevented by an omega profile between the gas cylinders. Figure 8.10(a) shows the cross-section of compartment 4 (cross-section EE of figure 8.1(a)), where the added omega profile is marked J.

![Cross-section of compartment 4](image1)

(b) Cross-section of compartment 2

Figure 8.10 - Cross-sections EE and DD of figure 8.1(a)

After modification of the model, the buckling analysis is performed again. Results can be found in figure 8.3. The right side wall and bottom of compartment 2 will buckle. The buckling load multiplier is 0.5.

![Buckling of undercarriage in a crash](image2)

Figure 8.11 - Buckling of undercarriage in a crash

A rim is created along the edge of the side wall to prevent buckling. Figure 8.10(b) shows the cross-section of compartment 2 (cross-section DD of figure 8.1(a)). The bottom of the compartment under the ventilator leaves enough space for stiffening. For computation, an omega profile (M) is added on the bottom. In the MICU, the space between the two rectangular tubes in compartment 2 could also be filled with a block profile over the whole length or foam glued to the bottom to prevent buckling.
After modification of the model, a static stress analysis is performed. Results can be found in figure 8.12.

The buckling load multiplier is 0.6. Buckling now occurs in compartment 4. A rim is created along the edge of the side wall and along partition 34 in order to prevent buckling.

The buckling analysis is performed again. The top plate and side plate of compartment 4 buckle when the load is multiplied with 0.6. The left wall and top plate are stiffened in compartment 2, 3 and 4. Omega profiles I and K are added. They can be seen in figure 8.10(b), 8.6 and 8.10(a).

After modification of the model, the simulation is performed again. Buckling occurs in the top plate when the load is multiplied with 0.9. The MICU has a hole in the top plate at this point. In order to examine the behavior of the MICU in a crash, the hole is taken into account in the model. The part of the plate behind the hole is stiffened with two omega profiles (I in figure 8.2(b)).
The model is modified and static stress and buckling load simulations are performed. The results can be found in figure 8.13. The buckling load multiplier is 1.3 for this simulation.

![Image 1](a)

![Image 2](b)

Figure 8.13 - Stress and buckling of undercarriage in a crash after stiffening of left wall and top plate

When the normal load is applied to the MICU, results can be seen in figure 8.14.

![Image 3](a)

![Image 4](b)

Figure 8.14 - Stress and buckling of undercarriage under normal load
Buckling occurs when the load is multiplied with 2.5. In order to prevent buckling of partition 34, a connection between the hole in the partition between compartment 45 and the partition between 34 is made with plate (I) (see figure 8.2(b)). Simulation with this model results in buckling when the load is multiplied with 5.

The model is further optimized by reducing the plate thicknesses again. The top, bottom and side walls are made from 0.9 mm plate. Because the large area of these plates, the weight can is reduced by 2.5 kg. Furthermore, most partitions are 1.2 mm thick and the thickness of plates for the mechanism (A and B) can be reduced to 3 and 1.5 mm respectively. An overview of used plate thicknesses can be found in appendix J.

The model is further optimized by adding a triangular part to the top plate. This can be seen in figure 8.15. The first simulation with this model resulted in a buckling load multiplier of 0.8. Buckling of the top plate occurs in the triangular part between the wide and small part of the top plate. This is prevented with a simple omega profile. The next simulation results in a buckling load multiplier of 1. Buckling of the top plate occurs in compartment 3. Figure 8.15 shows this result. The top plate is shown with the omega profiles and parts of the partitions.

Figure 8.15 - Buckling of undercarriage in a crash
Another omega profile is added to prevent this problem (R in figure 8.6). This finally results in a maximum stress of 240 N/mm² and a buckling load multiplier of 1.2 in a crash. The undercarriage can resist a 24 g crash. Results can be seen in figure 8.16.

Figure 8.16 - Stress and buckling of undercarriage in a crash
Under normal load, a maximum stress of 77 $N/mm^2$ is reached and buckling occurs when the load is multiplied with 4.8. Results can be seen in figure 8.17. Therefore, the load can be almost 5 times as high as the normal load.

Figure 8.17 - Stress and buckling of undercarriage under normal load
The undercarriage weighs 78 kg now. The weight can be reduced by cutting holes in some plates. Plates with relatively little stress can be bored. And some plates must be reduced. For example the side plate at the front needs a hole for storage of the defibrillator (265 x 225 mm). Holes in the plates make it able to reach the equipment easily and connect electrical connections and tubes. The holes must be made large enough to stick your hand through it (150 x 100 mm). Holes can be made in the plates for the mechanism (A and B). The hole in plate A may be filled with a thin plate in order to keep the oil of the cylinders in this compartment in case of leakage. The plate behind the monitor can contain a hole, even as in partition 12.

The end plate of the gas cylinder tunnel is 3 mm thick. Holes with a diameter of 100 mm can be made in this plate (the cylinders have a diameter of 150 mm. The partition cylinder tunnel may reach to the bottom plate of the undercarriage in order to keep the oxygen in the cylinders away from the batteries. The guiding for the tray of the gas cylinders can be fixed in the side wall of the cylinder tunnel. This fixation must also be strong enough to hold the cylinders in a backward crash.

Another kind of information the finite element simulations deliver is information about stresses in the connections to other parts of the model. This can help to decide whether plates are welded to each other or bent from one part. This last option is only possible when the same plate thickness is used. The side walls and the bottom can be bent from one plate. Because this line is loaded in a crash, a strong connection is reached in this way.

The rectangular tubes in the corners of the undercarriage can be created in three ways. These options can be found in figure 8.18.

![Figure 8.18 - Three options for construction of rectangular tubes in undercarriage](image)

Figure 8.18(a) shows a rectangular tube that is fixed in the corners of the undercarriage. A strong and stiff construction is made in this way, but the tube does not contain more stress as the side walls of the MICU (see figure 8.19). Therefore, the double wall thickness at this place is unnecessary. Rectangular tubes of this size can only be delivered with a wall thickness of 3 and 4/mm [4]. In figure 8.18(b), the side plate of the gas cylinder tunnel is used as the side wall of the rectangular tube. An apart plate is welded between the two plates. The last option is a bent plate that forms the inner side wall of the tube. This form is welded in the corner of the undercarriage. Both options (see figure 8.18(b) and 8.18(c)) are used. The side wall of the cylinder tunnel can be made from one part. The top plate of the tube is made in one part. Where the gas cylinder tunnel ends, this top plate is bent and the rectangular tube is constructed as in figure 8.18(b).
The mounting of the hydraulic cylinders, the top plate and back plate of the undercarrige can be seen in figure 8.20. The connection between the partitions 45 and 34 (J) can be bent from the partition 45 where the hole in this partition is made. Relatively high stress is present in this connection. The rest of this part must be welded against this part. Making part J from one plate is preferred. The weld is made in such a way that the partition is pushed against the connection between partition 34 and 45 (J).

As can be seen in figure 8.20, stress in the back part of the top plate and the back plate is relatively high. These two parts could be made from one plate, so the connection is a bent plate and not a weld. The top plate is divided in two parts.

Use of merlons (see figure 3.4(b)) makes it able to weld the construction without welding fixtures. Furthermore, strength and stiffness of the material is found instead of a weld.

Steel is chosen as standard material for the prototype of the MICU because of easy welding. Further reduction of weight can be reached when the MICU is made of aluminium.
Chapter 9

Loading the MICU in the ambulance

At the start of the project, loading the MICU in the ambulance seemed to be the largest problem. Various concepts were considered (see appendix H). A tailboard on the ambulance came out as the best option. This part of equipment is mounted on the ambulance. This reduces the weight of the MICU. Furthermore, a tailboard is commercially available, which results in a reasonable price and service by the manufacturer. The price of a tailboard varies from 4 till 6 k euro. Because the ministry of health care in the beginning of the project promised to pay for 10 Intensive Care ambulances equipped with a tailboard, further investigation was unnecessary. In the next section chapter, some points of attention when using a tailboard are mentioned and in section 9.2, an alternative for lifting the MICU in the ambulance, when a tailboard is not present, is described.

9.1 Tailboard

Three points of attention are considered in this section:

- **Fixation** The MICU must be fixated on the tailboard in order to prevent rolling away when lifting the tailboard. This can be done by grabbing the bottom of the MICU or the front wheels. And when the tailboard is long enough, a rim behind the back wheels is enough. The fixation on the tailboard must be made in such a way, that only driving in the ambulance is possible when loosening the fixation and rolling back cannot happen.

![Figure 9.1 - Fixation of the MICU on the tailboard](image)

Figure 9.1(a) shows two wedges (B) in the bottom of the MICU (A). When the MICU is driven on the tailboard, the first wedge will open and let the MICU drive over the rail (C) on the tailboard. When the wedge at one side is opened again, the MICU can be loaded in the ambulance without the risk of driving back. Figure 9.1(b) shows another alternative. The horse shoe formed part D is mounted on the tailboard and part E on the MICU. Part E
could be a wheel or an aprt pipe on the MICU. When the MICU is driven on the tailboard
(see vector v in (1)), it will stop in part D. When part D is rotated, no movement in driving
direction is possible (2). When part D is rotated further, the MICU could continue its way
to the ambulance.

**Guidance** The MICU is placed right in front of the fixation in the ambulance. Manoeuvring is
easier outside the ambulance.

A lot of different tailboards are available, even tailboards that are as long as the MICU (2 meter).
When the tailboard is shorter, the MICU must be supported. This can be done with a roll on the
tailboard (figure 9.2(b)) or with a fifth wheel under the MICU (figure 9.2(c)).

![Figure 9.2 - Three options for tailboard](image)

### 9.2 Loading the MICU without a tailboard

In order to lift the MICU in the ambulance with a minimal adaptation on the MICU (when a
tailboard is not available), two cylinders are mounted in the console and one telescopic cylinder is
mounted in one of the front compartments of the MICU. When the MICU is parked just before
the ambulance, the MICU is lifted to the height of the ambulance floor on the three cylinders.
When the cylinder is actuated to maximum height, the stiffness is determined by the fits in the
cylinder and is therefore stiffer. A connection to the ambulance can be made by a rack or a rail
that is mounted to the MICU. The connection to the ambulance in figure 9.3 has a wheel to drive
the MICU in the ambulance. The telescopic cylinder is drawn back and the MICU is driven on
the wheels on the two cylinders in the console and the wheels on the connection to the ambulance.

![Figure 9.3 - Loading the MICU in the ambulance](image)
Chapter 10

Conclusions and recommendations

10.1 Conclusions

Providing intensive care for critically ill children can best be done in tertiary centers. This centralization of care requires transport of the patients from the referring hospital to the tertiary facility centers. The MICU designed in this masters thesis enables transport teams to transport the patients in a safe and easy way. Previous prototypes were not crashworthy.

In discussion with the 8 tertiary centers in the Netherlands, the lay-out of the equipment on the MICU is determined. All equipment is stored in the undercarriage. The lay-out of the equipment provides a good sight on the equipment and enables to the transport team to reach all equipment, but also provides an optimized concentration of mass and a low center of gravity, which is essential for stability and crashworthiness.

The wheels on the MICU provide good driving properties and enables the transport team to park the MICU besides the bed of the patient in the referring hospital. Because all equipment is stored in the undercarriage, no equipment is stored on the bed and the patient can be reached from all sides. A mechanism is designed to lift the bed from ambulance position to working position, but also provides trendelenburg and anti-trendelenburg positions. Furthermore, the mechanism is crashworthy.

The bed can be taken apart from the mechanism. And because the bed is fully made of epoxy fiber composite, x-rays can be taken without lifting the patient. The patient can be crashworthy fixated on the bed.

The fixation of the MICU in the ambulance provides energy absorption in a crash. When a 20 $g$ crash occurs, an extra brake path of 100 $mm$ is provided where the energy is absorbed in deformation of the energy absorbers.

The construction of the undercarriage is optimized for a 20 $g$ crash.

A safe and easy to use mobile intensive care unit has been designed. A prototype of the MICU will be build by the GTD at the TU/e. Further development will be done in conversation with the tertiary centers.
10.2 Recommendations

- Interhospital transport can be improved when the installed apparatus needed to provide advanced life support and emergency treatment are made suitable for transport. Most apparatus are unnecessarily large and the connectors sticking out of the apparatus require more space to build in the equipment for transport. Furthermore, more efficient transport apparatus can be made when only one battery and one screen is used for all apparatus.

- Lifting the MICU in the ambulance can easily be done with a tailboard on an ambulance. This requires an extra investment for intensive care ambulances, but is the best option to lift the MICU in the ambulance, because no extra constructions (and weight) in the MICU is needed and tailboards are commercially available.

- In this masters thesis, safe transport of the patient on and equipment in the MICU is treated. A crashworthy fixation of the transport team that allows them to move in the ambulance and around the patient and minimizes the forces on their body in a crash is needed to save this vital human capital.

- The fixation of the MICU in the ambulance and of the patient on the bed can also be applied in normal hospital transport.
Bibliography


Appendix A

Wheels

A.1 A combination of rigid and swiveling castor

In order to have a combination of rigid and swiveling castors, three options to lock the rotation of castors are presented in figure A.1.

![Figure A.1 - Options for locking of swivel](image)

In figure A.1(a), a small wheel (C) is mounted on a leafspring (D), which is mounted on the swivel fork (B). In the bottom of the MICU (F), two wedges (G) fill two rectangular holes. When the MICU is manoeuvred, the rotation of the swivels is free. The wedges are now closed and the wheel drives on the bottom of the MICU. In normal drive situations, only two swivels and two castors are more desirable. With a handle or a pedal, the wedges are pulled up and now a hole occurs in the bottom of the MICU. When the swivels rotate when driving forward, the leafspring will force the wheel to lift and fall in the whole. The rotation of the swivel is now locked. When the wheel needs to be rotated again, the handle or paddle is used again, to push the wedges back to the bottom of the MICU. This will allow the wheel (C) to drive freely on the bottom of the MICU and the big wheel (A) to swivel. The rotation of the wheel is now locked on a large radius. This makes the force on the locking mechanism small and the play of the wheel in terms of rotation small. In this option, the small wheel (C) always drives on the bottom of the MICU and is preloaded with the leafspring.

A second option is presented in figure A.1(b). A ring H is mounted in the bottom of the MICU.
(F). When the swivel is free, the small wheel (C) rotates together with the wheel (A) and the swivel fork (B) without the preload of the leafspring (D). Preload of the wheel on the ring will only occur when the ring (H) is pushed down and the wheel is forced to drive on the ring. Because two slits are made in the ring, the wheel and leafspring will fall in these slits and lock the rotation of the swivel. When the ring (H) is pulled up again, the wheel freely swivels. With this option, the preload on the wheel (C) only occurs when we want to lock the swivel. The rotation of the ring (H) must be fixed and lowering and lifting of the ring must happen without tilting.

A more simple mechanism would be desired and is found in option c (see figure A.1(c)). A ring (L) is mounted on the swivel fork (B). A lever (I) is rotating around a fixed turning point under the MICU. On the lever, a wheel (J) is fixed in the sandwich of the lever. This lever could be given a bi-stable mechanism, in order to have two positions: rolling around the ring (L) or laying on a present (aanslag) under the box. Or the operation handle of the mechanism would have two positions in order to make the wheel (J) free from the ring (K) or not. When the swivel is rotating freely, the wheel (J) is not driving along the ring (L). A handle is operated, and the spring (K) will push the lever and the wheel against the ring. When the wheel (A) is in driving forward position, the hole in the ring is rotated to the wheel and the spring will push the ring into the whole. The rotation is now locked. When the handle is operated again, the wheel is pulled out of the hole in the ring. A rather simple mechanism is designed now.

### A.2 Information on Colson Medical Castors

The properties of medical castors of type combi - total and directional lock are presented in table A.1.

<table>
<thead>
<tr>
<th>wheel diameter [mm]</th>
<th>max. load [kg]</th>
<th>tire material</th>
<th>code</th>
<th>weight [kg]</th>
</tr>
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<tbody>
<tr>
<td>125</td>
<td>135</td>
<td>Grey Polyurethane</td>
<td>2-5513-409-004-0001-0805</td>
<td>1.67</td>
</tr>
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<td>150</td>
<td>Grey Polyurethane</td>
<td>2-6513-409-004-0001-0805</td>
<td>2.20</td>
</tr>
<tr>
<td>125</td>
<td>90</td>
<td>Grey Rubber</td>
<td>2-5513-409-004-0001-0202</td>
<td>1.67</td>
</tr>
<tr>
<td>150</td>
<td>100</td>
<td>Grey Rubber</td>
<td>2-5513-409-004-0001-0202</td>
<td>2.20</td>
</tr>
</tbody>
</table>

Table A.1 - Properties of Colson medical castors
Appendix B

List of equipment

**Monitoring**

- ECG,
- respiratory rate,
- pulse oximetry,
- temperature,
- blood pressure non-invasive (cuffs neonatal, infant, child, adult),
- blood pressure invasive,
- capnography, point-of care blood testing

**Defibrillator**

- 5-400 J capacity with pediatric and adult paddles

**Airway management**

- Laryngoscope with blades Miller 0-1 and Macintosh 1-4,
- Magill forceps (pediatric and adult),
- endotracheal tubes (uncuffed 2.0-6.0 and cuffed 5.0-8.0),
- endotracheal tube stylettes,
- oral airways 0-5,
- suction unit and suction catheters,
- stethoscope,

**Ventilatory management**

- Chest tubes and Heimlich valve,
- nebulizer,
- oxygen delivery devices (nasal cannulas, oxygen masks),
- artificial humidifier,
- resuscitation bags (child and adult),
- PEEP valve,
- face masks (infant, child, adult),
- mechanical ventilator (neonatal, pediatric, adult)
APPENDIX B. LIST OF EQUIPMENT

---

**Gas supplies**

Oxygen and air, with pre and post pressure regulator manometer, flowmeter 15 L/min plug-ins for oxygen and air in ambulance and referring hospital

---

**Fluid management**

Intravenous cannulas, intra-osseous needles, central venous lines, infusion pumps, fluids (normal saline, 5% dextrose), tubing, needles, syringes

---

**Medication**

Pulmonary: bronchodilators aerosol, salbutamol for iv, corticosteroids
Circulatory: adenosine, atropine, calcium chloride, diuretics, dobutamine, dopamine, epinephrine, norepinephrine, amiodarone, lidocaine, sodium bicarbonate, vasodilators
Neurologic: anticonvulsant, mannitol, muscle relaxants, naloxone, opiate, sedative
Other: antibiotics, clemastine, colloids, 50% dextrose, potassium, medication for all possible derangement

---

**Electrical power**

---

**Plug-in connection in ambulance and referring hospital**

---

**Other materials**

Adhesive tape, arterial line maintenance system, nasogastric tubes (6,8,10,12 Fr), urinary bladder catheters (infant, child, adult), scissors, alcohol wipes, flashlight, resuscitation chart, patient chart, communication equipment

---

Taken from table 1 chapter 4 from [1]
Appendix C

Drive of scissor lift

In this appendix, an option for actuation of the scissor lift (see figure 4.2(d) in chapter 4.1) is explained.

A schematic drawing of this drive mechanism in the ambulance position can be seen in figure C.1. A beam (A) is fixed between the two legs (G). Pulling these beams towards each other results in lifting the bed. Two rods (B) are connected to the beams (A) and to two nuts (C). Because one part of the screw (D) is left-hand screw thread and the other part is right-hand, rotating the screw results in moving the nuts towards each other or away from each other. A relatively small force between the nuts (C) results in a relatively large force between the beams A. Because the transmission ratio for lifting the bed with a force between the beams A becomes more advantageous during this movement and the transmission ratio for pushing the beams A towards each other becomes less advantageous, a constant moment can be found to drive this mechanism.
Appendix D
Calculation of forces on the mechanism

In order to dimension the forces on the mechanism as a function of the parameters listed in table D.1, a free body diagram of the mechanism can be seen in figure 4.6 on the next page. Equilibria of forces and moments are used to determine these forces.

**Forces acting on the bed**

$F_l$ works in the $z$-direction. The force $F_p$ works under an angle of $\alpha_h$ with respect to the $x$-axis, because this force can only work in the axial direction of beam 2. $F_q$ is split up in a horizontal and a vertical component, $F_{q,x}$ and $F_{q,z}$ respectively.

Equilibrium of moments with respect to point $q$ yields:

$$F_l \cdot x \cos \alpha_h = F_p \cdot h \cos(\alpha_h - \delta) \quad (D.1)$$

This equation can be rewritten to a definition of $F_p$:

$$F_p = \frac{x \cos \alpha_h}{a \cos(\alpha_l - \delta)} \cdot F_l \quad (D.2)$$

$F_{q,x}$ and $F_{q,z}$ can be determined from force equilibrium in $x$ and $z$-direction:

$$F_{q,x} = F_p \cos \alpha_h \quad (D.3)$$
$$F_l = F_p \sin \alpha_h + F_{q,z} \rightarrow F_{q,z} = F_l - F_p \sin \alpha_h \quad (D.4)$$

The radial load on the bearings in $q$ can be determined from $F_{q,x}$ and $F_{q,z}$:

$$F_q = \sqrt{F_{q,x}^2 + F_{q,z}^2} \quad (D.5)$$

**Forces acting on beam 1**

The reaction force of $F_q$ on beam 1 can be split up in an axial force $F_{ax,1}$ and a transversal force $F_{tra,1}$:

$$F_{ax,1} = \cos \alpha_h F_{q,x} + \sin \alpha_h F_{q,z} \quad (D.7)$$
$$F_{tra,1} = \sin \alpha_h F_{q,x} + \cos \alpha_h F_{q,z} \quad (D.8)$$
APPENDIX D. CALCULATION OF FORCES ON THE MECHANISM

Figure D.1 - Forces on mechanism

<table>
<thead>
<tr>
<th>symbol</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_h$</td>
<td>Height angle (angle between horizontal and beam 1)</td>
</tr>
<tr>
<td>$\alpha_t$</td>
<td>Trendelenburg angle (angle between horizontal and bed)</td>
</tr>
<tr>
<td>$\gamma_h$</td>
<td>Start angle of height actuation</td>
</tr>
<tr>
<td>$\gamma_t$</td>
<td>Start angle of trendelenburg actuation</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Angle of line through p and q with respect to the bed</td>
</tr>
<tr>
<td>$F_{\text{act},h}$</td>
<td>Actuation force for height adjustment</td>
</tr>
<tr>
<td>$F_{\text{act},t}$</td>
<td>Actuation force for trendelenburg adjustment</td>
</tr>
<tr>
<td>$F_l$</td>
<td>Weight of patient on bed</td>
</tr>
<tr>
<td>$F_d$</td>
<td>Radial force on bearing in point d</td>
</tr>
<tr>
<td>$F_p$</td>
<td>Radial force on bearing in point p</td>
</tr>
<tr>
<td>$F_q$</td>
<td>Radial force on bearing in point q</td>
</tr>
<tr>
<td>$F_r$</td>
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<tr>
<td>$F_s$</td>
<td>Radial force on bearing in point s</td>
</tr>
<tr>
<td>$a$</td>
<td>Distance between points p and q</td>
</tr>
<tr>
<td>$l$</td>
<td>Length of beams</td>
</tr>
<tr>
<td>$x$</td>
<td>Distance between rotation point of bed and load $F_l$</td>
</tr>
</tbody>
</table>

Table D.1 - Explanation of symbols in figure D
Equilibrium of moments with respect to s yields:

\[ F_{\text{tra},1}l = F_{\text{act},h}a_h \cos(\alpha_h - \gamma_h) \]  

(D.9)

This equation can be rewritten to

\[ F_{\text{act},h} = \frac{F_{\text{tra},1}l}{a_h \cos(\alpha_h - \gamma_h)} \]  

(D.10)

The forces on point s in x and z-direction can now be determined:

\[ F_{s,x} = F_{\text{ax},1} \cos \alpha_h + F_{\text{tra},1} \sin \alpha_h + F_{\text{act},h} \]  

(D.11)

\[ F_{s,z} = -F_{\text{ax},1} \sin \alpha_h + F_{\text{tra},1} \cos \alpha_h \]  

(D.12)

So the radial force on point s yields:

\[ F_s = \sqrt{F_{\text{ax},1}^2 \cos^2 \alpha_h + F_{\text{tra},1}^2 \sin^2 \alpha_h + F_{\text{act},h}^2 - F_{\text{ax},1}^2 \sin^2 \alpha_h + F_{\text{tra},1}^2 \cos^2 \alpha_h} \]  

(D.13)

Definitions from goniometry:

\[ \cos 2\alpha = \cos^2 \alpha - \sin^2 \alpha = 1 - 2 \sin^2 \alpha = 2 \cos^2 \alpha - 1 \]  

(D.14)

\[ \cos^2 \alpha + \sin^2 \alpha = 1 \]  

(D.15)

are used to rewrite (D.13)

\[ F_s = \sqrt{F_{\text{ax},1}^2 \cos 2\alpha_h + F_{\text{tra},1}^2 + F_{\text{act},h}^2} \]  

(D.16)

**Forces acting on beam 2**

The axial load on beam 2 is \( F_p \).

**Forces acting on trendelenburg bar**

Equilibrium of moments with respect to d

\[ F_{\text{act},t}a_t \cos(\alpha_t - \gamma_t) = F_p \cos \alpha_h \cos(\alpha_t + \delta)a + F_p \sin \alpha_h \sin(\alpha_t + \delta)a \]  

(D.17)

is used to determine the horizontal actuation force for the trendelenburg adjustment \( F_{\text{act},t} \):

\[ F_{\text{act},t} = F_p \frac{a \cos \alpha_h \cos(\alpha_t + \delta) + \sin \alpha_h \sin(\alpha_t + \delta)}{\cos(\alpha_t - \gamma_t)} \]  

(D.18)

Equilibria of forces in x and z-direction are used to determine the load on bearing d:

\[ F_{d,x} = F_p \cos \alpha_h + F_{\text{act},t} \]  

(D.19)

\[ F_{d,z} = F_p \sin \alpha_h \]  

(D.20)

\[ F_d = \sqrt{F_p^2 + F_{\text{act},t}^2} \]  

(D.21)
**Optimization of start angles \( \alpha_h, \alpha_t \) and \( \delta \)**

In order to optimize the layout of the mechanism, the formulas will be rewritten in terms of the load \( F_l \).

\((D.2)\) can be substituted in \((D.4)\):

\[
F_{q,z} = \left(1 - \frac{x}{a} \cos \alpha_h \sin \alpha_h\right) \cdot F_l
\]

\((D.2)\) can also be substituted in \((D.3)\):

\[
F_{q,x} = \frac{x}{a} \cdot \frac{\cos^2 \alpha_h}{\cos(\alpha_t - \delta)} \cdot F_l
\]

\((D.6)\) can be rewritten by substitution of \((D.4)\) and \((D.3)\) and then \((D.2)\) can be substituted:

\[
F_q = \sqrt{(F_p \cos \alpha_h)^2 + (F_l - F_p \sin \alpha_h)^2}
\]

\[
= \sqrt{F_p^2 \cos^2 \alpha_h + F_l^2 - 2F_l F_p \sin \alpha_h + F_p^2 \sin^2 \alpha_h}
\]

\[
= \sqrt{\frac{x \cos \alpha_h}{a \cos(\alpha_t - \delta)} \cdot F_l^2 + \frac{F_l^2}{a \cos(\alpha_t - \delta)} - 2 \frac{x \cos \alpha_h}{a \cos(\alpha_t - \delta)} \cdot F_l \sin \alpha_h}
\]

\[
= F_l \sqrt{\frac{x^2}{a^2} \cdot \frac{\cos^2 \alpha_h}{\cos^2(\alpha_t - \delta)} + 1 - 2 \frac{x}{a} \frac{\cos \alpha_h \sin \alpha_h}{\cos(\alpha_t - \delta)}}
\]

\((D.7)\) can be rewritten by substitution of \((D.4)\) and \((D.3)\):

\[
F_{ax,1} = F_p \cos^2 \alpha_h + F_l \sin \alpha_h - F_p \sin^2 \alpha_h
\]

The goniometry formula as stated in \((D.14)\) and \((D.2)\) can be used to rewrite \((D.25)\) as:

\[
F_{ax,1} = F_p \cos \alpha_h + F_l \sin \alpha_h = (\frac{x}{a} \cdot \frac{\cos \alpha_h \cos 2\alpha_h}{\cos(\alpha_t - \delta)} + \sin \alpha_h) F_l
\]

\((D.8)\) can be rewritten by substitution of \((D.4)\) and \((D.3)\):

\[
F_{tra,1} = \sin \alpha_h F_p \cos \alpha_h + \cos \alpha_h (F_l - F_p \sin \alpha_h) = F_l \cos \alpha_h
\]

Equation \((D.10)\) can be rewritten by substitution of equation \((D.27)\):

\[
F_{act,h} = \frac{\cos \alpha_h}{\cos(\alpha_h - \gamma_h)} \cdot \frac{l}{a_h} \cdot F_l
\]

\((D.18)\) can be rewritten by substitution of \((D.2)\):

\[
F_{act,t} = \frac{x \cos \alpha_h}{a_t \cos(\alpha_t - \delta)} \cdot F_l \frac{\cos \alpha_h \cos(\alpha_t + \delta) + \sin \alpha_h \sin(\alpha_t + \delta)}{\cos(\alpha_t - \gamma_t)}
\]

Another goniometry rules tells:

\[
\cos \alpha \cos \beta + \sin \alpha \sin \beta = \cos(\alpha - \beta)
\]

and therefore:

\[
\cos \alpha_h \cos(\alpha_t + \delta) + \sin \alpha_h \sin(\alpha_t + \delta) = \cos(\alpha_h - (\alpha_t + \delta)) = \cos(\alpha_h - \alpha_t - \delta)
\]
Substitution of (D.31) in (D.29):

\[
F_{act,t} = \frac{x \cos \alpha_h}{a_t \cos (\alpha_t - \delta)} \cdot F_l \frac{\cos (\alpha_h - \alpha_t - \delta)}{\cos (\alpha_t - \gamma_t)} \tag{D.32}
\]

Now all the equations are known in terms of the load, optimization can be performed. The results of this optimization can be found in section 4.3.
Appendix E

Dimensioning of axles

E.1 Dimensioning of axle q in beam 1

<table>
<thead>
<tr>
<th>Dimensions of axle</th>
<th>Geometrical properties</th>
<th>Bending stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{a,o}$</td>
<td>$D_{a,i}$</td>
<td>$D_{b,o}$</td>
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<tr>
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<td>16</td>
<td>20</td>
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<td>25</td>
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<tr>
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<td>22.5</td>
<td>30</td>
</tr>
<tr>
<td>48.3</td>
<td>23.5</td>
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</tr>
<tr>
<td>51</td>
<td>29</td>
<td>30</td>
</tr>
</tbody>
</table>

Table E.1 - Bending stress in axle q in beam 1

The thick walled tube 44.5 x 22.5 mm and the end with outer diameter 30 mm form a stiff axle. For this construction, the deflection is calculated with ALGOR:

The deflection of this axle is 0.018 − 0.014 = 0.004 mm under this load.
## E.2 Dimensioning of axle r in trendelenburg bar

<table>
<thead>
<tr>
<th>Dimensions of axle $[\text{mm}]$</th>
<th>Geometrical properties $\times 10^4 [\text{mm}^4]$</th>
<th>Stress $[\text{N/mm}^2]$</th>
<th>rotation angle $[\text{[°]}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{a,o}$ $D_{a,i}$ $D_{b,o}$</td>
<td>$I_a$ $I_d$ $I_p$ $W_a$ $W_d$ $W_p$</td>
<td>$\sigma_d$ $\sigma_b$ $\sigma_w$ $\phi_w$ $[\text{[°]}]$</td>
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<td>145 95 33 0,34</td>
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<tr>
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</tr>
<tr>
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<td>48,3 0,504 96,7 17,0 0,336 33,9</td>
<td>486 29 10 0,069</td>
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</table>

Table E.2 - Stress in axle r

The deflection of the beam is computed with ALGOR:

![Figure E.2 - Deflection of axle in trendelenburg bar](image)

The deflection is $0.18 - 0.06 = 0.12 \text{ mm}$
Appendix F

DU-B bearings

Figure F.1 - Projected area

Figure F.2 - Parameters of DU-B bearings
### Figure F.3 - Fitting of flanged bushes

#### Table F.1 - DU-B bearings

<table>
<thead>
<tr>
<th>part no.</th>
<th>Nominal Diameter</th>
<th>Bush Wall $D_i$</th>
<th>Flange Wall $D_f$</th>
<th>Flange-Diam. $S_f$</th>
<th>Length $B$</th>
<th>Shaft-Diam. $D_J$</th>
<th>Housing-Diameter $D_H$</th>
<th>Bush inside diam. $D_1$</th>
<th>Clearance $C_D$</th>
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<td>50</td>
<td>44,99</td>
<td>45,105</td>
<td>0,015</td>
</tr>
</tbody>
</table>
Figure F.4 - Friction coefficient of DU-B bearings
Appendix G

Energy absorption in bending of a strip

The amount of energy that can be absorbed in plastic deformation of the bending strips as in figure 7.2(a) is calculated in this section. In bending, the plastic strain $\varepsilon_{pl}$ depends on the height in material. The strain is assumed to be constant over the length and width of the strip. The width of the strip b is constant. The absorbed energy in bending can now be described as

$$E_{abs} = \sigma_y b l \int |\varepsilon_{pl}(y)| \, dy \quad (G.1)$$

The strain in the strip is examined using figure G.1. The strip is not elongated at the neutral axis of the strip. The length of the strip along the neutral axis is called the bending allowance ($L_b$). The distance between the outer fiber on the smallest radius and the neutral axis is defined as $kR$, where $R$ is the bending radius of the strip. $k$ lies between 0.33 ($R < 2T$) and 0.5 ($R > 2T$) [14]. $T$ is the thickness of the strip, $\alpha$ is the bending angle.

The strain at the outer fibers can be calculated using the length of arc $L$ in figure G.1. The length of the strip at the outer fibers and at the neutral line can be described as:

$$L_{max} = \frac{\alpha}{360} 2\pi (R + T) \quad (G.2)$$

$$L_b = \frac{\alpha}{360} 2\pi (R + kT) \quad (G.3)$$

$$L_{min} = \frac{\alpha}{360} 2\pi (R) \quad (G.4)$$

the strain at the outer fibers is:

Figure G.1 - Dimensions of strip
and for the strain as a function of the height in the strip $y$ can be written:

$$
\epsilon(y) = (y - kT) \frac{\epsilon_{max}}{(1 - k)T} = (y - kT) \frac{1}{1 - k} T = \frac{(y - kT)}{(1 - k)T} \tag{G.7}
$$

The plastic strain is defined as $\epsilon_{pl} = \epsilon - \epsilon_{el}$. For $y$ between $0$ and $kT - t_{el}$ and between $kT + t_{el}$ and $T$, the elastic strain equals the maximum elastic strain and therefore, the plastic strain can be defined as: $\epsilon_{pl} = \epsilon - \epsilon_{el,max} = \frac{(y-kT)}{(R+kT)} - \epsilon_{el,max}$. The absolute value of the plastic strain is defined as:

$$
|\epsilon_{pl}| = \begin{cases} 
\frac{-y+kT}{R+kT} - \epsilon_{el,max} & \text{for } 0 < y < kT - t_{el} \\
0 & \text{for } kT - t_{el} < y < kT + t_{el} \\
\frac{y-kT}{R+kT} - \epsilon_{el,max} & \text{for } kT + t_{el} < y < T 
\end{cases}
$$

Because the plastic strain is zero around the neutral axis, (G.1) can be rewritten to:

$$
E_{abs} = \sigma_y b h \left\{ \int_0^{kT-t_{el}} |\epsilon_{pl}| \, sb \, dy + \int_{kT+t_{el}}^T |\epsilon_{pl}| \, dy \right\} \tag{G.8}
$$

$t_{el}$ can be computed by substitution of $\epsilon(t_{el} + kT) = \epsilon_{el,max}$ in (G.7),

$$
\epsilon_{el,max} = \frac{(y-kT)}{(R+kT)} \rightarrow t_{el} = \epsilon_{el,max} (R+kT) \tag{G.9}
$$

(G.8) can now be rewritten.
\[ E_{\text{abs}} = \sigma_{\text{y}} b l \left\{ \int_{0}^{k T - t_{\text{cl}}} \left( -y + \frac{k T}{R + k T} - \epsilon_{\text{el,max}} \right) dy + \int_{k T + t_{\text{cl}}}^{T} \left( y - \frac{k T}{R + k T} - \epsilon_{\text{el,max}} \right) dy \right\} \]

\[ = \sigma_{\text{y}} b l \left\{ \left[ \frac{\frac{1}{2} y^2 + k T y}{R + k T} - \epsilon_{\text{el,max}} \right]_{0}^{k T - t_{\text{cl}}} + \left[ \frac{\frac{1}{2} y^2 - k T y}{R + k T} - \epsilon_{\text{el,max}} \right]_{k T + t_{\text{cl}}}^{T} \right\} \]

\[ = \sigma_{\text{y}} b l \left\{ \frac{T^2 - k T^2 + k^2 T^2}{R + k T} + \epsilon_{\text{el,max}} (2t_{\text{cl}} - T) \right\} \]  

(G.10)

(G.9) is inserted and an expression for the energy in the bending of a strip as a function of \(T, R, k\) and \(\epsilon_{\text{el,max}}\) is found:

\[ E_{\text{abs}} = \sigma_{\text{y}} b l \left\{ \frac{1}{2} T^2 - k T^2 + k^2 T^2}{R + k T} + \epsilon_{\text{el,max}} (R + k T) - \epsilon_{\text{el,max}} T \right\} \]  

(G.11)

The force on the hammer that deforms the strip can be calculated using this equation. Equation (G.11) describes the energy to bend a strip with width \(b\) over 180° over a length \(l\). The strips used in the fixture of the MICU (see figure 7.2(a)) are deformed twice (bending and bending back). The strip is deformed at both sides of the hammer. The absorbed energy equals the work needed to deform the strips \(E_{\text{abs}} = W = F \cdot s\). When the hammer A moves over a length \(s\), the deformed length of the strip is only the half of this length \(s\): \(\frac{1}{2} s = \frac{1}{2}\). The force acting on the strip during deformation can therefore be expressed as:

\[ F = \frac{2}{s} E_{\text{abs}} = \sigma_{\text{y}} b l \left\{ \frac{1}{2} T^2 - k T^2 + k^2 T^2}{R + k T} + \epsilon_{\text{el,max}} (R + k T) - \epsilon_{\text{el,max}} T \right\} \]  

(G.12)

This equation can be used to dimension the strips needed in the energy absorbing fixtures of the MICU. Further information can be found in section 7.2

G.1 Tensile test

A tensile test is performed in order to characterize the material behavior of the strips. Two strips cut (from the same plate as the strips for the energy absorber) are narrowed, so the strip will break in this part of the strip and not in the clamps. The strip is colored with ink and stripes are marked 5 mm from each other. This can all be seen in a picture of the strips after the test (see in figure G.3).

![Figure G.3 - Strips after tension test](image-url)
The data from the test can be seen in figure G.4.

Conclusions from this figure are:

- The elastic energy in the strip is very small with respect to the plastic energy. \( \epsilon_{el,max} = \frac{0.1 \text{ mm}}{105 \text{ mm}} = 0.000952 \).

- Fracture will occur when the strip is elongated 20 mm.

- Strain is defined as \( \epsilon_{avg} = \frac{\ell - \ell_0}{\ell_0} \). The initial length \( \ell_0 \) can be determined by measuring the distance between the first and the last mark. For strip 2, this is 105 mm. And the initial length is 15 times 5 mm or 75 mm. The marks can be seen on strip 2. Average strain \( \epsilon_{avg} = \frac{105 - 75}{75} = 0.4 \) for strip 2 and \( \epsilon_{avg} = \frac{88.5 - 60}{60} = 0.47 \) for strip 1.

- The strain around the contraction is \( \epsilon_{max} = \frac{21 - 10}{10} = 1.1 \) for strip 1 and 2.

- The maximum stress \( \sigma_{max} = \frac{F}{A} = \frac{18.9 \text{ kN}}{20 \text{ mm} \times 3 \text{ mm}} = 315 \text{ N/mm}^2 \) for strip 1 and \( \sigma_{max} = \frac{18.5 \text{ kN}}{20 \text{ mm} \times 3 \text{ mm}} = 308 \text{ N/mm}^2 \). This is the normal stress and not the true stress based on the actual area. This differences is due to differences in initial area, true area or due to differences between the material.

- Because only two strips have been tested, statistically nothing can be said about these strips, but assuming that the yield stress \( \sigma_y = 315 \text{ N/mm}^2 \) and that strains of 50% can be reached without fracture seems reasonable.
G.1.1 Testing of energy absorption strips

In this section, the results of the test as presented in section 7.3 are shown. Figure G.5 zooms in on the data in figure 7.6 in section 7.3.

The following remarks can be made from this test:

- Although statistic certainty cannot be reached from a test with 5 strips, we may conclude a force of about 14.5 kN is needed to deform the strip and 1.45 kJ of energy can be absorbed per strip over 100 mm.

- The force needed to deform the strip is higher than expected. In the calculation, the energy in elastic deformation, friction, warmth was not calculated. Because of the cold strengthening of the strip, the second deformation requires more energy. This was not taken into account in the calculation.

- When these strips are made in one production step with a large hydraulic press, the deformation and cold strengthening is more local, so the force needed to deform the strips will be more constant. Deforming the first part of the strip before mounting in the fixtures is another option when a more constant force is desired.

- A higher deformation rate will result in a higher force because of cold strengthening.

- The strip does not perfectly fold around the plunger. Look at figure G.6 to see the round form of the strip. This is due to spring back. The first bending of the strip cannot be totally bent back and this form occurs.

- When the strip is stress-relieved by annealing, the force may be more constant during the test. About 90% stress relief may be possible when the strip is heated in an oven of 600° for 6 hours. Because this heat treatment could also result in decarbonization, the strip is packed in cast iron curls. This was not enough to keep air out of the way, so strip 4 is rusted on one side. Stress relief is not reached as can be seen in figure 7.6. The yield strength will lower because of the heat treatment. This can be seen in a lower force to deform the preformed material. The final force, however, is higher for this strip with 14.7 kN, but its not very constant.

The strips after deformation can be seen in figure G.6.
Figure G.6 - Tested energy absorbing strips (1 till 5 from left to right)
Appendix H

Concepts for loading of MICU into the ambulance

H.1 Basic concepts

(a): In figure H.1 the three basic ways of making a MICU with equipment are shown. H.1(a) shows the traditional way of making a stretcher. The patient is moved on a bed (A) which is lying on a foldable undercarriage (C). The big advantage of this concept is the fact, that all the weight is already on the right height to drive it into the ambulance. This is also the biggest disadvantage of this concept. Almost the entire weight is high above the ground. The equipment is perfectly reachable when walking next to the MICU. The undercarriage carries all the weight, which requires a strong and stiff frame. A stiff wheel suspension is hard to make using this concept, and driving the wheels is not that easy.

(b): Figure H.1(b) shows a new concept, where all heavy materials that need transport on the Mobile Intensive Care Unit are in a an undercarriage (B). The wheels are mounted on this undercarriage. A mechanism (D) can be used to support the bed and the patient, which is only $\frac{1}{3}$ of the total weight of the MICU. The center of gravity is lower to the ground than it was for concept (a). If we assume the center of gravity for concept (a) to be on 950 mm above the ground, in the middle of the bed and on 550 mm above the ground for concept (b), the maximum corner to tilt the MICU before it turns over is 20° and 36°, respectively. But, when applying this concept, we need to find a way to lift the MICU into the ambulance very easy.

(c): Combining the easy-loading feature of concept (a) and stability and driveability of concept (b) brings us to a concept where the equipment is close to the ground when driving, but can be lifted just under the bed to drive it in the ambulance very easily. The frame (E) requires a lot of space in the undercarriage and carries the whole weight, as in concept (a). This can be seen in
H.2 Concept (a): Equipment under the bed

Figure H.2 shows three options using basic concept (a) can be seen.

(a1): The first one is the traditional way of making a stretcher. Except for the advantage that the undercarriage is commercially available and is therefore relatively cheap, only disadvantages can be found. The last support must be folded in very soon when loading the MICU. From that point, the MICU needs to be lifted by hand. Of course, an extra supporting wheel could prevent this. In order to make a stiff frame, the construction points must be well divided over the brancard.

(a2): In order to prevent folding in the last support when the bed is not entirely in the ambulance, concepts (a2) and (a3) can be found. Concept (a2) contains legs that are connected to a stiff pipe (E), which is lying in the undercarriage B. A stiff mount for the legs can be realized. The folding-in movement is now made to the outside of the MICU and the legs can support the MICU till it is almost entirely in the ambulance. Folding the legs around the axle perpendicular to the longitudinal direction is another option. This last option does not require opening 180 degrees of the doors of the ambulance.

(a3): Driving the MICU into the ambulance without lifting could also be done when the first leg can be shifted under the MICU.

H.3 Concept (b): Equipment on the ground

In figure H.3 two basic options for driving the MICU into the ambulance can be seen.

(b1): The MICU can be lifted horizontally (b1) or the undercarriage (B) can be rotated by lifting up at one side or pushing up at the other side. In that case, the patient must stay horizontal.

(b2): In case of option b1, the bed stays horizontal, but in case of b2 the bed (A) must be rotated with respect to the undercarriage (B). In the following subsections, some options on this concepts will be presented.
H.3.1 Concept (b1): Lifting upright

Figure H.4 shows six different options on concept (b1).

(b1.1): A first option, which combines the vertical movement of lifting and the horizontal movement of driving the MICU into the ambulance, is a four bar mechanism under the MICU (b1.1). When starting to lift the MICU, a horizontal force is needed on point s. This may be produced by friction between the ground and the bar between r and s. The mechanism must be actuated over its unstable upright position in order to set the first wheels of the MICU in the ambulance. This will lift up point r. The parallelogram could be actuated by a cylinder which is the diagonal of the four bar mechanism. However, when assuming a height of 700 mm for the ambulance floor and a length of the horizontal bar of 1400 mm, the diagonal requires a large stroke, from about 450 till 1250 mm. In this case, we have already assumed that the legs of the mechanism can be enlarged from 300 mm (needed to fit under the undercarriage B) to 700 mm to lift the MICU higher than the ambulance floor.

Another option for actuation of (b1.1) is using a winch. The cable is fixed onto the undercarriage (B), near point q and leaded around a roll in point r and than back to the winch in the ambulance. In this way, the MICU can be lifted with the part of the cable between the ambulance and q and set down easily on the ambulance floor using the part of the cable between r and q. As a conclusion we could say the movement of the four bar mechanism is the right one and the bed stays perfectly horizontal. But the bars of the mechanism should be telescopic or the basis (distance between p and q) should be very small, which makes it less stable. Differences in height of the ambulance floor can only be reached by rotating further than vertical. Last but not least it requires a rather heavy construction onto the MICU.

(b1.2): Another possibility is a sliding rail (D) as in figure H.4, which is mounted in the ambulance. The rail is pulled outside the ambulance and mounted to the MICU. In order to do that, the height of the MICU is adjusted. The MICU does not need difficult mechanisms or constructions. But to carry the MICU, a rather heavy rail or tube is needed. Such a heavy rail of, for example, 2 meter extendible to 3 meter, is needed on both sides of the MICU.

(b1.3): Options b1.3 and b1.4 from figure H.4 are very different from the first two. In these cases, the bed (A) is first layed upon the undercarriage (B). The whole folded MICU is now lifted with a crane E as in (b1.3), where four cables F are fixed on the corners of the undercarriage (B).

(b1.4): For option (b1.4), an arm as in a refuse-lorry is used to lift the MICU into the ambulance.
Both options require adaptation of the ambulance. But more important is, that it requires a lot of space in the ambulance near the patient, where space is needed for treatment of the patient.

**(b1.5):** When looking for a construction to lift the MICU from the outside of the ambulance, we may think of a tailboard. Again, the MICU is folded and driven on the tailboard using its own drive system. When anchored to the tailboard, the tailboard is lifted to the height of the ambulance floor. Now the MICU can be driven into the ambulance. This option (b1.5 from figure H.4) will need some adaptations on the ambulance, but will not require space in the inside of the ambulance. Furthermore, no constructions on the MICU are necessary as only to fix it on the tailboard.

**(b1.6):** A last option is presented as option (b1.6). A sort of lorry is clicked under the MICU, when it was still standing upright. Point u of the lorry (see figure H.4, (b1.6)) is connected first and the lorry is rotated under the bed (A) this point v of the lorry is also connected. The other point of the bed is fixed on the ambulance on point t. Now the bed is secured, the undercarriage (B) can be lifted. When this box is directly under the bed, the whole MICU is driving on the wheels in point w and the guiding of point t into the ambulance. At last, points v and u are disconnected from the bed and the lorry may be taken away and stored in a compartment of the ambulance.

The tailboard (b1.5) is the best option to lift the MICU into the ambulance, because it is simple, cheap and reliable. Furthermore, no extra heavy equipment is needed on the MICU.

### H.3.2 Concept (b2): Undercarriage inclined, bed lifted upright

**(b2.1):** The most simple way of driving something on wheels into a van is possibly making use of a steel planking. This is option b2.1 in figure H.5. When an inclination of 1:4 is used, a length of more than 2,5 meter is needed to drive the MICU into the ambulance. Another disadvantage of this option is the bottom height needed to be able to drive over the angle between steel planking and ambulance. A solution for that problem could be found in making a jointed undercarriage.

**(b2.2):** Another option is to lift or push the MICU up and set the first wheels into the ambulance. Than the other wheels of the undercarriage (B) are lifted and the MICU can be driven into the ambulance. An extending rod would do that very good, but a stroke of 700 mm in the undercarriage does not seem to be an option. In option b2.2, a supporting leg S is under the MICU and can be rotated. Because the back wheels are on the brakes, the wheel W rides on the ground towards the back wheels. This action lifts up the front of B. Now the MICU can be driven on the back wheels and the supporting wheels W to the ambulance and the front of the undercarriage is fixed in the ambulance. Further rotation of S around t makes the undercarriage become horizontal again. A rather long leg is needed to lift the MICU 700 mm above the ground. From start position (on the ground, before the ambulance) till the front wheels are fixed in the ambulance, wheel W must be between the ambulance and the center of gravity of the MICU in order to stand stable on the support wheel. This bending construction will be rather heavy. An advantage of this concept is that the angle between the ground and the undercarriage B can be directly coupled to the desired angle between the undercarriage and the bed in order to keep the patient horizontally. Furthermore, this way of lifting the MICU with a self braking drive seems
to be more safe for the patient than a wench and a cable under large tension as presented in, for example, b1.1.

(b2.3): With option b2.3, a mechanism is made, which pushes up the front of the MICU at the front and the back at the back. Furthermore, the bar between i and j offers lateral stiffness to the bar between h and j and vice versa. In start position, point i is translated over rail R towards point g. Therefore, the wheel at point j pushes to the ground and lifts the MICU. A rather bad ratio is used here to lift the MICU. And in start position, the lifting force is not very far from the middle, because the MICU has to be lifted 700 mm which is the minimum length of the bars. When the MICU is lifted, driven to the ambulance and the front wheels are fixed, point i can be translated back to point g. Now point h can be translated over the rail R towards f. When the MICU is horizontal, it can be driven into the ambulance. The wheels can be folded when the bars are disconnected at j. The both bars can be rotated and pushed in the undercarriage. When applying option b2.3, long rails, actuators and bearings will be necessary. These parts require a lot of space in the undercarriage.

H.4 Concept (c): Equipment can be lifted to the bed to drive into the ambulance

In figure [H.6] four options on concept c are presented. In every concept, the undercarriage (B) is lifted till it is just under the bed (A). In that case, the legs can be hinged and folded in. This can be done using gearwheels as in figure H.6 c1. We could also use some sort of american bumper jack as in (c2). A disadvantage of this system is the noise it makes when clicking in safety palls. Maybe a better option is using the construction of a car inspection lift (c3). The undercarriage is lifted upright. Material is used very efficiently, because only tensile stress is brought into the material, so every fibre of the cable is used. Also in this case, safety palls will be needed and make the well known 'inspection lift noise'. A last option is mounting hydraulic cylinders on the wheels to push up the undercarriage.
Appendix I

Construction drawings

Trendelenburg bar

Section AA (scale 1:2)

Section AA (scale 1:2)

Section BB (scale 1:1)
Axle s and r

as r (schaal 1:2.5)
Axle p and q
Table I.1 - Parts of beam 1

1. U-formed plate
2. Bottom plate
3. Upper plate
4. Height adjustment plate
5. Reinforcement for height adjustment
6. Reinforcement for top of beam
7. Hole for height adjustment actuator
8. Hole for axle cd
Appendix J

Plate thickness of undercarriage

<table>
<thead>
<tr>
<th>Description</th>
<th>Algor group</th>
<th>mark</th>
<th>thickness [mm]</th>
</tr>
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<tbody>
<tr>
<td>Back plate</td>
<td>1</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Side plate front</td>
<td>2</td>
<td></td>
<td>0,9</td>
</tr>
<tr>
<td>Outer plate for mechanism</td>
<td>230</td>
<td>B</td>
<td>1,5</td>
</tr>
<tr>
<td>Side plate back</td>
<td>4</td>
<td></td>
<td>0,9</td>
</tr>
<tr>
<td>Bottom</td>
<td>5</td>
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<td>0,9</td>
</tr>
<tr>
<td>Wheel houses</td>
<td>6</td>
<td></td>
<td>0,9</td>
</tr>
<tr>
<td>Partition 45</td>
<td>7</td>
<td></td>
<td>1,2</td>
</tr>
<tr>
<td>Partition 34</td>
<td>8</td>
<td></td>
<td>1</td>
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<tr>
<td>Plate above cylinders</td>
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<td>C,D</td>
<td>1</td>
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<td></td>
<td>0,8</td>
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<tr>
<td>Inner plates for mechanism</td>
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<td>A</td>
<td>3</td>
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<tr>
<td>Plate behind monitor</td>
<td>12</td>
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<tr>
<td>Partition 23</td>
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<td>Compartment for perfusion pumps</td>
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<td></td>
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<td>Front plate</td>
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<td>Plates around module rack</td>
<td>17</td>
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<td>1</td>
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<tr>
<td>Parts of partition cylinder tunnel and partition 23</td>
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<td></td>
<td>3</td>
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<tr>
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<tr>
<td>Stiffening plate for partition 12</td>
<td>33</td>
<td>P</td>
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<tr>
<td>Mounting for hydraulic cylinders</td>
<td>39</td>
<td>F</td>
<td>4</td>
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<tr>
<td>Horizontal plate at mounting of hydraulic cylinders</td>
<td>40</td>
<td>G</td>
<td>1</td>
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<tr>
<td>Omega profile</td>
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<td>H,I</td>
<td>0,35</td>
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<tr>
<td>Omega profile</td>
<td>56</td>
<td>H,I</td>
<td>0,35</td>
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<tr>
<td>Connection between partitions 45 and 34</td>
<td>57</td>
<td>J</td>
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<td>Mounting of wheels</td>
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<td>Rectangular tube</td>
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<tr>
<td>Bottom of rectangular tube</td>
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<td>S</td>
<td>0,9</td>
</tr>
<tr>
<td>side wall of rectangular tube</td>
<td>202</td>
<td>D</td>
<td>0,9</td>
</tr>
<tr>
<td>Outer plates for mechanism</td>
<td>230</td>
<td>B</td>
<td>1,5</td>
</tr>
</tbody>
</table>

Table J.1 - Plate thickness used in Finite element simulation
## Appendix K

### List of symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
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<tbody>
<tr>
<td>$\alpha$</td>
<td>angle</td>
<td>$^\circ$</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>relative strain</td>
<td>$-$</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>stress</td>
<td>$N/mm^2$</td>
</tr>
<tr>
<td>$\phi$</td>
<td>rotation angle</td>
<td>$rad$</td>
</tr>
<tr>
<td>$A$</td>
<td>area</td>
<td>$mm^2$</td>
</tr>
<tr>
<td>$a$</td>
<td>acceleration</td>
<td>$m/s^2$</td>
</tr>
<tr>
<td>$c$</td>
<td>stiffness</td>
<td>$N/mm$</td>
</tr>
<tr>
<td>$D$</td>
<td>diameter</td>
<td>$mm$</td>
</tr>
<tr>
<td>$E$</td>
<td>modulus of elasticity</td>
<td>$N/mm^2$</td>
</tr>
<tr>
<td>$E_{abs}$</td>
<td>absorbed energy</td>
<td>$J$</td>
</tr>
<tr>
<td>$E_{kin}$</td>
<td>kinetic energy</td>
<td>$J$</td>
</tr>
<tr>
<td>$F$</td>
<td>force</td>
<td>$N$</td>
</tr>
<tr>
<td>$f$</td>
<td>deflection</td>
<td>$mm$</td>
</tr>
<tr>
<td>$g$</td>
<td>gravitation</td>
<td>$m/s^2$</td>
</tr>
<tr>
<td>$k$</td>
<td>relative position of the neutral axis of a strip</td>
<td>$-$</td>
</tr>
<tr>
<td>$I$</td>
<td>second moment of area</td>
<td>$mm^4$</td>
</tr>
<tr>
<td>$M_b$</td>
<td>bending moment</td>
<td>$Nm$</td>
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<tr>
<td>$p$</td>
<td>pressure</td>
<td>$N/m^2$</td>
</tr>
<tr>
<td>$R$</td>
<td>radius</td>
<td>$mm$</td>
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<tr>
<td>$s$</td>
<td>travel</td>
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<tr>
<td>$W_b$</td>
<td>section factor for bending</td>
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Samenvatting

Recente ontwikkelingen in het aanbieden van intensive care voor kinderen vraagt om centralisatie van deze zorg in specialistische centra. Kritisch zieke kinderen zijn er beter aan toe als ze behandeld zijn in een tertiair pediatrisch centrum dan wanneer ze behandeld zijn in een ander pediatrisch centrum. Deze centralisatie van zorg vereist transport vanuit het verwijzende ziekenhuis naar het tertiair pediatrisch centrum. Gespecialiseerde transport-team nemen alle apparatuur en benodigheden mee om tijdens het stabiliseren voorafgaand aan het transport en tijdens het transport het niveau van de zorg zo dicht mogelijk bij dat van de pediatrische intensive care (PICU) te brengen. In het academisch ziekenhuis in Maastricht (AZM) is een mobiele unit ontwikkeld, gebaseerd op een normaal branocard-onderstel. Het gebruik van een dergelijke unit om de benodigde apparatuur, medicatie en de patiënt te vervoeren blijkt zeer succesvol, maar de stabiliteit en veiligheid van deze unit is onvoldoende.

Probleemstelling:

Ontwerp een mobiele intensive care unit (MICU) die het transport team in staat stelt de apparatuur, medicatie en de patiënt op een veilige en handige manier te transporteren.

De eisen aan een dergelijke unit zijn onderzocht en aan de hand daarvan zijn ontwerp principes opgesteld. In samenspraak met de 8 tertiaire centra in Nederland is de indeling van de apparatuur vastgesteld. Alle apparatuur en medicatie is opgeborgen in het onderstel. De apparatuur is zo geplaatst, dat het goed zichtbaar en bereikbaar is voor het transport team. Bovendien is de apparatuur zo ingedeeld, dat een laag zwarepunt en een concentratie van de massa bereikt wordt. Deze laatste twee aspecten zijn essentieel voor de stabiliteit en de botsveiligheid. De wielen onder de MICU zorgen voor goede rij-eigenschappen en maken het mogelijk om makkelijk naast het bed van de patiënt te parkeren. Door middel van de rem op de wielen kan worden voorkomen dat de MICU wegrolt. Omdat alle apparatuur in het onderstel geplaatst is, is het bed rondom helemaal vrij. De patiënt kan daardoor van alle kanten benaderd worden. Er is een mechanisme ontworpen, dat het bed vanuit de ambulancedeur naar de werkstand kan tillen. Het bed kan ook draaien naar de trendelenburg en anti-trendelenburgstand. Ook het mechanisme is botsveilig. Het bed kan van het mechanisme afgehaald worden. En omdat het bed volledig van epoxy vezel composiet gemaakt is, kan men röntgenfoto’s van de patiënt maken zonder hem naar een ander bed te moeten tillen. De patiënt kan botsveilig gefixeerd worden op het bed.

In de fixatie van de MICU wordt kinetische energie geabsorbeerd. In een 20 g botsing wordt er energie opgenomen over een extra remweg van 100 mm. De constructie van het onderstel is geoptimaliseerd voor een botsing met 20 g. Er is een veilige en makkelijk te gebruiken intensive care unit ontworpen. Een prototype van de MICU zal gemaakt worden bij de GTD van de TU/e. Verdere ontwikkelingen zullen in samenspraak met de 8 tertiaire centra gedaan worden.
Dankwoord