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ELECTRIFICATION OF HYDRAULIC LINEAR ACTUATORS

Master of Science Thesis
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ABSTRACT

Tuukka Pakarinen: Electrification of hydraulic linear actuators
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The objective of this thesis is to determine the extent to which electromechanical linear actuators (EMLA) can meet the requirements of hydraulic linear actuators (HLA) in mobile working machines (MWM). The European Union (EU) and governments are accelerating the electrification due to environmental concerns by directing original equipment manufacturers (OEM) towards it through decisions and subsidies.

The public catalogs of OEMs of EMLAs and MWMs are used to collect the specifications and to define the requirements and performance characteristics of EMLAs. Based on them, the comparative quality function deployment (QFD) analysis is performed, which seeks to determine the relative rankings of the most competitive EMLAs. The understanding of the EMLA market is also facilitated by the OEM-specific requirement tables and the specification tables which include more OEMs than the QFD analysis.

Maximum dynamic force of an EMLA is the most significant performance characteristic. Classified according to it, two OEMs, Creative Motion Control and Motiomax, are capable of manufacturing EMLAs which can produce maximum dynamic forces of more than 1000 kilonewtons. Dynamic forces exceeding this limit are needed in a wide range of MWMs. Based on the QFD analysis and the specifications, Motiomax, Creative Motion Control and Ewellix can manufacture the most competitive EMLAs which can operate as a part of a MWM.

Keywords: Electromechanical linear actuator, mobile working machine, maximum dynamic force, quality function deployment

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TIIVISTELMÄ

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Tämän diplomityön tarkoituksena on selvittää, missä määrin sähkömekaaniset lineaaritoimilaitteet (engl. electromechanical linear actuator, EMLA) voivat täyttää hydraulisten lineaaritoimilaitteiden (engl. hydraulic linear actuator, HLA) vaatimukset liikkuvissa työkoneissa (engl. mobile working machine, MWM). Euroopan unioni ja hallitukset kiihdyttävät alkuperäisten laitevalmistajien (engl. original equipment manufacturer, OEM) tuotteiden sähköistämistä ilmastonmuutosta hidastamaan pyrkivillä päätöksillään ja tuillaan.

EMLA:iden ja MWM:ien OEM:ien julkisesti saatavilla olevia tuotekatalogeja käytetään spesifikaatioiden keräämiseen ja EMLA:iden vaatimusten ja suorituskykyominaisuuksien määrittämiseen. Niiden pohjalta suoritetaan vertaileva asiakaslähtöisen tuotekehityksen (engl. quality function deployment, QFD) analyysi, jonka tavoitteena on selvittää kilpailukykyisimpien EMLA:iden suhteellinen paremmuusjärjestys. EMLA-markkinoiden ymmärtämistä helpottavat myös OEM-kohtaiset vaatimustaulukot ja spesifikaatiotaulukot, jotka sisältävät enemmän OEM:ien tuotteita kuin QFD-analyysi.

Dynaaminen maksimivoima on merkittävin EMLA:n suorituskykyyn vaikuttava ominaisuus. Sen mukaan luokiteltuna Creative Motion Control ja Motiomax kykenevät valmistamaan EMLA:ita, jotka pystyvät tuottamaan yli 1000 kilonewtonin dynaamisen maksimivoiman. Tämän rajan ylittäviä dynaamisia voimia tarvitaan monenlaisissa MWM:ssä. QFD-analyysin ja spesifikaatioiden perusteella Motiomax, Creative Motion Control ja Ewellix valmistavat tämän hetken kilpailukykyisimmät EMLA:t, jotka kykenevät toimimaan osana MWM:ää.

Avainsanat: Sähkömekaaninen lineaaritoimilaite, liikkuva työkone, dynaaminen maksimivoima, asiakaslähtöinen tuotekehitys

Tämän julkaisun alkuperäisyys on tarkastettu Turnitin OriginalityCheck –ohjelmalla.

PREFACE

This Master's thesis was composed as a part of a research project in Tampere University. I want to thank my thesis examiners Jouni Mattila and Saku Mäkinen, who offered me the interesting topic and guidance for my writing process. I also want to thank my close ones for their support during the writing process and my colleagues at work.

Tampere, on December 9th, 2021

Tuukka Pakarinen

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LIST OF SYMBOLS AND ABBREVIATIONS

CMC	*Creative Motion Control*
COTS	*Commercial-of-the-shelf*
CpM	*Cycles per minute*
DpY	*Days of operation per year*
EU	*European Union*
HLA	*Hydraulic linear actuator*
HOQ	*House of quality*
HpD	*Hours operated per day*
MWM	*Mobile working machine*
OEM	*Original equipment manufacturer*
PV	*Pressure velocity*
QFD	*Quality function deployment*
TCO	*Total cost of ownership*
VOC	*Voice of customer*

A	*Effective area of hydraulic linear actuator*
C	*Dynamic load capacity*
d_s	*Diameter of roller or ball screw*
F	*Force*
F_{maxdyn}	*Maximum dynamic force*
$F_{maxstat}$	*Maximum static force*
h_{max}	*Maximum height of parallel drive electromechanical linear actuator*
IP	*Ingress protection class*
l	*Length of electromechanical linear actuator*
L_{10}	*Life cycle in km that 90% of identical electromechanical linear actuators can be expected to reach, calculated with 200 kN equivalent dynamic force*
m_0	*Weight at 0 mm stroke*
m_{100}	*Weight per 100 mm stroke*
M_{max}	*Maximum allowable input torque*
p	*Rated system pressure*
P	*Screw lead*
s_{max}	*Maximum stroke length*
T	*Permissible ambient temperature*
v_{max}	*Maximum linear velocity*
w_{max}	*Maximum width of electromechanical linear actuator*
η	*Mechanical efficiency of roller or ball screw*

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1. INTRODUCTION

The current development trend is to get rid of polluting internal combustion engines in the mobile working machines (MWM). These off-road machines have been powered by mobile hydraulic rotary actuators in their hydrostatic transmissions and in their so-called working hydraulics composed of multi-link manipulators and end-effectors are typically equipped with hydraulic linear actuators (HLA) (Lajunen et al., 2018).

In the first phase of this sustainability development, so-called battery electric vehicles (BEV) are introduced, where the on-board internal combustion engines have been replaced with battery driven electric motor drivelines in similar fashion to electric cars. With respect to working hydraulics, electric motors are installed to rotate the hydraulic pumps for supplying existing working hydraulic circuits. Generally, rotating hydraulic actuators are easier to be replaced by electromechanical actuators, especially in applications where volumetric size and weight of an actuator are not an issue in design. This can be case, for example, in the wheeled loaders, tracked excavators and bulldozers where additional vehicle body weight is sometimes added for its better drivability and stability (Lajunen et al., 2018).

Therefore, in the less mature second phase of MWM development, the question is if the working hydraulics are also meaningful to be replaced with electromechanical linear actuators (EMLA) towards complete electrification. Generally, electrification of linear motion actuators has been seen as very challenging, due to the numerous MWM requirements that HLAs can fulfil in the current applications. The requirements make this study necessary, and these are such as: high force capacity, high linear velocity, compact size, high power to own weight ratio, low cost, tolerance to high impact forces and safety functions such as load holding. (Ewellix, 2021c; Lajunen et al., 2018; Sandvik 2021b; Tolomatic 2021b).

1.1 Background

Plethora of industries from transportation vehicles to aviation are undergoing the transformation with electrification which is also pushed by the European Union (EU) and the governments. For example, in the mining industry, the electrification is facilitated by many innovations, such as automatic battery swap technology, extending battery life, increasing voltage, or improving the capacity and reliability of equipment. The same innovations can be applied almost entirely to the whole transportation sector. In line with sustainable development, the electrified mining equipment significantly improves health and safety issues compared to the previous technologies, by producing less noise, heat, and vibration or by eliminating hazardous exhaust gases. Harsh mining environment also present challenges in the form of the protection of electrified equipment. This can be taken into account by selecting the EMLAs with the appropriate ingress protection (IP) ratings. The IP ratings grade the resistance of a housing against the intrusion of dust or liquids. (IEC, 2021; Lajunen et al., 2018; McFadden, 2021)

On the other hand, electric motors including their EMLA transmissions are commonly claimed to have high-efficiency, good controllability, higher precision, minimal need for maintenance, no leakages or contamination, and lower long-term costs (Tolomatic, 2021b). In this thesis, these well-known claims are investigated by making the market review and technical assessment of the commercial-off-the-shelf (COTS) EMLAs available to see if they can meet the requirements, especially in terms of load capacity and harsh outdoors conditions relevant to Finland-based MWM original equipment manufacturers (OEM).

1.2 Scope and methods

This thesis seeks to discover an answer to the research question of how properly EMLAs can meet the requirements of current HLAs in MWMs. The issue is important because the EU and governments are directing OEMs towards wider electrification through decisions and subsidies due to environmental concerns (Lajunen et al., 2018).

The broad task is also to examine the market situation for EMLAs. Full electrification is not yet possible on the largest MWMs (Kalmar, 2019b; Ponsse, 2021; Sandvik, 2021b; Volvo Construction Equipment, 2017) due to the insufficient dynamic forces of EMLAs, so it is important to determine the extent to which the performance characteristics of EMLAs are sufficient. Therefore, the objective is to map the most competitive EMLAs from the most advanced OEMs at high load capacity range. The EMLAs in MWMs most often operate outdoors, so they must also be suitable for the applications that face intrusion from dust and liquids.

The specifications and performance characteristics of the EMLAs on the market are compared, based on the information available on websites and public catalogs of the OEMs.

The suitability and competitiveness of the EMLAs are determined based on the performance characteristics and their requirements, and the comparison is continued by the QFD analysis to determine how the performance characteristics of the most competitive products success in relative to each other.

This thesis is arranged as follows. The second chapter focuses on heavy-duty off-road MWMs in terms of their characteristics and challenges in electrification transition, considers the advantages and disadvantages of the EMLA as a replacement for a HLA and introduces the proper sizing of an EMLA. Chapter 3 introduces the structure of EMLA in terms of its critical parts, screw and bearing, considers the characteristics of mountings and brakes and presents the comparable EMLA OEMs and their products. The products of these OEMs are considered in the final QFD analysis in chapter 5. Chapter 4 describes the analysis methods of the thesis and represents the performance characteristics of EMLAs utilized in the analysis. Chapter 5 provides the results of the work and the calculations leading to them and proceeds as follows. The specifications of the EMLAs on the market are tabulated. From them, the most suitable products are distinguished for comparison and the requirements are set for them. In the final comparative QFD analysis, weighted ratings are provided for the critical performance characteristics that ultimately determine the best EMLAs on the market. Chapter 6 summarizes the content of the work and includes possible ideas for future research avenues on the topic.

2. ELECTROMECHANICAL LINEAR ACTUATORS ON HEAVY-DUTY OFF-ROAD MOBILE WORKING MACHINES AND AS REPLACEMENTS FOR HYDRAULIC LINEAR ACTUATORS

The heavy-duty off-road working machines, or mobile working machines (MWM), are on a turning point as they are step by step going to be completely and intelligently electrified. The greater part of MWMs operates in harsh environment where dust and water are intruding the equipment. Next, different off-road MWMs on the market are compared briefly in terms of their characteristics and challenges in electrification transition.

2.1 Off-road mobile working machines

Leguan Lifts, part of the Finnish Avant Tecno Group, manufactures self-propelled access platforms (Figure 1) for lifting persons. According to the company's (Avant Tecno Oy, 2021) catalog, the linear actuators of the access platforms are required to perform with excellent safety, be able to work outdoors, and withstand moderate maximum lifting capacity of 230 kg. The access platforms cannot be classified as heavy-duty machines, so the electrification of their linear actuators seems to be very feasible. The speed requirement of the lifting movement of the outrigger is not very high, but a locking system is required to keep the platform at a certain height. The stroke length of the linear actuator must also be sufficiently long to make it easier to achieve the high working heights of up to 19 meters. (Avant Tecno Oy, 2021).

Figure 1. *Leguan Lifts self-propelled access platform of Avant Tecno Oy (Avant Tecno Oy, 2021).*

Figure 2 shows the Beaver, the Ponsse's six-wheeled forest harvester, which has comparatively high requirements for the performance of the linear actuator. The linear actuator must move fast and handle the crane’s lifting moment of 230 kNm. The forest environment requires endurance in the harsh conditions from the linear actuator and does not provide access to a battery charging point, thus creating challenges for electrical operation. The maximum reach of 11 meters and this bring demands for the long stroke length of the linear actuator. (Ponsse, 2021).

Figure 2. *Ponsse Beaver forest harvester (Ponsse, 2021).*

Sandvik’s tunneling jumbos (Figure 3) operate in harsh mining conditions and are used in a wide range of drilling applications such as bolt hole drilling, face drilling and cross-cut drilling. The linear actuator must withstand high drilling forces and the resulting vibration. The boom of the Sandvik's smallest tunnel jumbo, the DT621, already weights 2100 kg, so high forces are required from the linear lifting actuators. The drilling also requires high precision in drill bit positioning, which at the same time increases the accuracy requirements of the linear actuator. (Sandvik, 2021a).

Figure 3. *Sandvik DT621 tunneling jumbo (Sandvik, 2021a).*

Sandvik's executives state in the McFadden's (2021) article that the electrification is already at an excellent pace, as the current diesel internal combustion engines and fuel tanks are being removed from the Sandvik's MWMs and replaced by batteries in the first phase of BEV technology. The second phase seeks to develop the full battery integration to optimize performance and efficiency, rethinking the whole machine and proceeding from wheels to other parts. (McFadden, 2021).

Compared to unstructured forest environment, it is easier to install battery charging points on a mine-by-mine basis. Technological developments in energy use and charge optimization ensure that the BEVs are at least as productive machines as their predecessors. Charging points have been developed for the mines with the automatic battery swapping system, which eliminates the downtime required for charging. Downtime has also been a problem with internal combustion engine driven machines as the fuel tanks needs to be filled. (McFadden, 2021).

Kalmar, part of the Cargotec Corporation, provides solutions for the handling of heavy cargo in ports, terminals, and distribution centers. Kalmar has already succeeded in fully electrifying an empty container handler with a maximum load in the center of gravity of 7,000 kilograms and has also fully electrified forklift trucks, terminal tractors, carriers, yard cranes and automated guided vehicles. Without compromising on performance, the empty container handler is designed to specifically reduce fuel costs and meet high airborne noise standards. The electrification with battery technology allows clean and efficient lifting and reduces the need for maintenance, the number of moving parts and wear compared to the preceding diesel internal combustion engine. The improved performance is reflected in full immediate torque and smooth operation, resulting in shorter cycles and thus more containers can be moved per hour. (Kalmar, 2019b).

Figure 4 shows Kalmar’s electric empty container handler and eco reachstacker. The next step for Kalmar could be the electrification of the reachstacker series with a nominal lifting capacity ranging from 10,000 to 70,000 kg. Since the operational role of reachstackers is similar with the electric empty container handlers, the benefits of electrification would also be similar to those mentioned above. However, higher load capacities place more challenges on the lift actuators and poses further challenges to the adequacy of actuator speed which affects the length of cycle. (Kalmar, 2021).

Figure 4. *Kalmar Electric Empty Container Handler (left) and Eco Reachstacker (right) (Kalmar, 2019a), (Kalmar, 2021).*

Kalmar’s reachstackers have a lot of intelligent solutions that make it easier to optimize the performance of the linear actuators. The Kalmar insight performance management tool measures accurate data on the operation of equipment, which also facilitates the sizing of the future actuators as accurate requirements can be formulated from the data for different performance characteristics. (Kalmar, 2021). According to Kalmar's electric container handler brochure (2019b), lithium-ion batteries can last in multi-shift operation. Automatic battery swapping technology could also be developed to eliminate downtime in ports and terminals.

In excavators, EMLAs face significant challenges due to impulses caused by ground contact impacts and high speed requirements. The first step in electrification is underway in small excavators, as shown by Volvo’s electric small excavator prototype, called the EX2. The completely electric prototype is emission-free and ten times more efficient and lower in noise levels than its predecessors, without compromising on performance characteristics. The EX2 also significantly decreases the total cost of ownership, produces as much force capability as conventional counterparts and is faster in its movements. (Volvo Construction Equipment, 2017).

Figure 5 shows fully electrified Volvo CE's compact excavator and Yanmar's eFuzion concept excavator. Japanese OEM Yanmar has unveiled an electrified eFuzion concept vehicle that demonstrates autonomous and accurate MWM with a robotic arm. The small concept excavator combines robotics, connectivity, autonomous and computer-assisted technologies and illustrates MWM's autonomous operations while performing excavator tasks and avoiding typical construction site obstacles. (Yanmar, 2019).

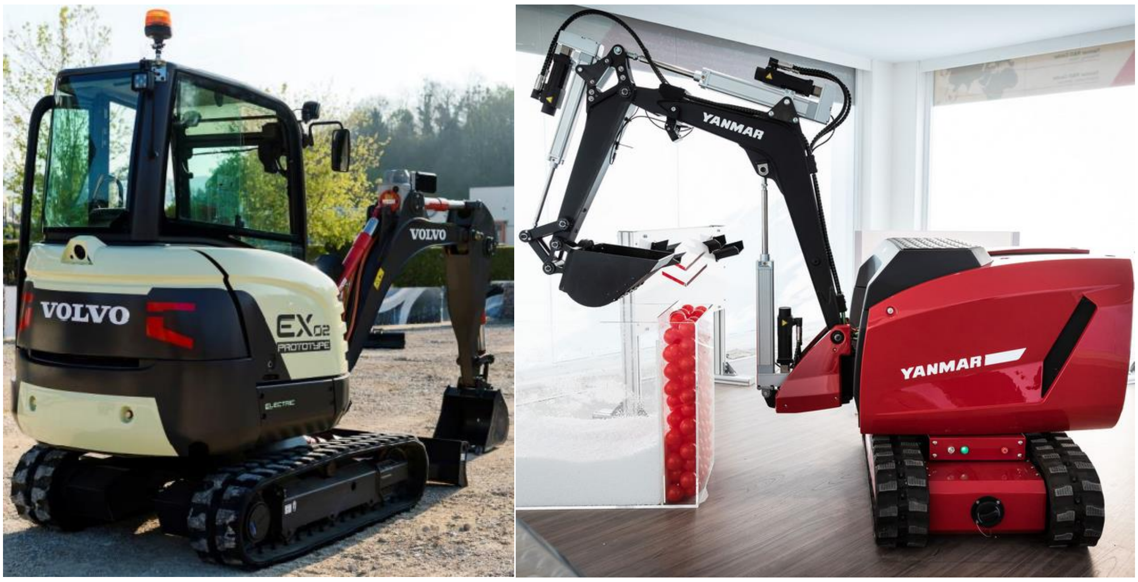


Figure 5. *Fully electrified Volvo CE's compact excavator and Yanmar's eFuzion concept excavator (Volvo Construction Equipment, 2017), (Yanmar, 2019).*

In summary, heavy-duty MWMs face very similar challenges and requirements in sustainable electrification. The uniform requirements include overcoming outdoor conditions, agile charging capabilities, long lasting performance, efficiency, and especially high load capacity from the linear actuators. EMLAs in the MWMs are also required to operate at different speeds, have high accuracy, long stroke lengths, safe operation, locking capability and impact and vibration resistance capabilities. The stroke length is usually less than one meter, but some applications require a longer stroke length, which can be accomplished especially with telescopic linear actuators.

The seals on the HLAs have a limiting effect on their maximum linear velocity, which is also required by the EMLA. Typically, standard seals for HLAs are capable of linear velocities up to 0,5 m/s. HLA seals for MWMs which are operating in harsh conditions place additional demands on the seals and can limit the linear velocity to 0,3 m/s. Linear velocities above 0,5 m/s often require standard low-friction seals, such as Teflon seals, which typically withstand linear velocities up to 1,0 m/s. High linear velocities of HLAs can also place additional requirements on the temperature resistance of the hydraulic system. (Hydroline, 2021b).

The forces of EMLAs are not sufficient for the heaviest MWMs so the high load capacity of HLAs is still required for large-scale applications. Hydroline and Norrhydro are Finnish OEMs of HLAs whose customers include companies in the forestry, mining, and load handling sectors. The previously mentioned companies Kalmar, Ponsse, and Sandvik are customers of both companies and HLAs are used on their medium and large sized MWMs. (Hydroline 2021a; Norrhydro, 2020). Hydroline and Norrhydro manufacture their products on a customer-specific basis, so the maximum forces for their HLAs are not available in public catalogs. However, the maximum forces of the products from both OEMs are indicated by the piston diameter and maximum pressure available on the websites of the OEMs. (Hydroline 2021c; Norrhydro, 2021a).

Calculated according to equation (1) in chapter 2.4, the maximum force of the Hydroline product would be almost 5000 kN, calculated with the maximum values of 300 mm piston diameter and 700 bar pressure. Correspondingly, Norrhydro's HLAs have the maximum piston diameter of 500 mm and the maximum pressure of 400 bar and thus the maximum force of almost 8000 kN. (Hydroline 2021c; Norrhydro, 2021a). The operating forces of HLAs on MWMs are significantly lower than those forces, but it is demonstrated that HLAs can have very high load capacity. The most competitive HLAs can push even greater forces, as Montanhydraulik's products point out. Designed for large excavators and cranes, among others, the lifting capacity of the Montanhydraulik’s HLAs can be up to 15,000 kN. (Montanhydraulik, 2021).

2.2 Actuators

Actuators are electromechanical or mechanical devices which produce controlled movements or positioning that are performed electrically, manually, or by air or hydraulics. Linear actuators convert energy into linear motion. Linear actuator trajectories generally include push and pull functions and they are commonly used in positioning applications. In addition to the linear motion, another basic motion of the actuators is the rotational motion. A rotary actuator converts energy to produce rotating motion. Actuators generally have different force configurations and vary in size and type depending on the application. (Thomas Publishing Company, 2021).

This thesis focuses on EMLAs that act as replacements for HLAs. The operation of the EMLAs is usually powered with an electric motor whose rotational motion is converted into a linear motion through a screw (Thomas Publishing Company, 2021). In addition to the electric motor and screw, the EMLA structure often includes a gear as part of the transmission. For example, with gear reduction of 2, the linear unit side (output) of the gear moves at half speed compared to the gear’s motor side (input). Gear reduction decreases electric motor torque requirements, allowing the use of smaller and cheaper electric motors. (Ewellix, 2021c).

In this study, due to the delimitation of the topic, the focus is on EMLA cylinder type linear units. The public OEM catalogs which are the source of the EMLA specifications also focus on the performance characteristics of the linear units, and motors and gears are offered as optional equipment.

2.3 Advantages and disadvantages of electromechanical linear actuators over hydraulic linear actuators

EMLAs convert the rotary motion of an electric motor into linear displacement while hydraulic forces are generated by fluids under pressure. The HLA technology has been the only option for decades if powerful linear forces have been needed. HLAs can provide high force, compact size, straightforward usage, and low cost per unit of force. (Tolomatic, 2021b). Table 1 summarizes the advantages and disadvantages of HLAs as pros and cons.

Table 1. *Pros and cons of HLAs.*

Hydraulic linear actuators	
Pros	Cons
High force capacity	Need for regular maintenance
High linear velocity	Leaks -> Environmental concerns
High power to own weight ratio	Poor reliability
Compact size	Loudness
Straightforward usage	Prone to temperature fluctuations
Low cost per unit of force	Complicate data collection
Simple design	Low positioning precision
Cheaper linear unit	Difficult speed controllability
	High linear velocity requires an expensive and complex system setup
	More components in system level
	High energy consumption
	Energy consumption while not in use
	Complex safety arrangements
	Higher total cost of ownership

Besides the simple design and the easily produced power, HLAs have few significant disadvantages. Without regular maintenance, HLAs will leak and could break, which causes unnecessary costs and safety issues. The fluids also cause environmental concerns and zero waste solutions have become more and more recommended for automation processes. HLA fluid power systems are noisy and susceptible to temperature fluctuations, as viscosity need to be consistently maintained by cooling or heating. The heat generation of HLAs is also higher than with EMLAs. (Ewellix, 2021c; Tolomatic, 2021b).

The use of an open-loop control complicates the data collection of HLAs. Accurate multi-positioning or speed and acceleration control are not possibilities without complex servo-hydraulic systems and additional sensors. HLAs also require more intricate external components to operate accordingly. Comparing to HLAs, EMLAs deliver better accuracy, reliability, and flexibility. EMLAs operate in a closed-loop environment, which enables accurate positioning and easy data collection. Closed-loop control does not need external sensors and settle time for positions is fast and repeatable. Thus, EMLAs can easily achieve high linear velocity, whereas HLAs require expensive and complex hydraulic system setups which at the same time increase energy consumption. (Ewellix, 2021c; Tolomatic, 2021b).

HLAs can generate powerful forces but those are usually achievable with EMLAs. Fluctuations in temperature do not affect to the performance of EMLAs and they and they do not require the warm-up time that HLAs may require. This improves the productivity of the EMLA. The whole predictable life cycle of EMLA hardly at all requires any maintenance and causes no contamination worries for the ambient environment. A hydraulic fluid-powered system has more critical equipment such as a compressor, pumps, motors, noise-reduction equipment, heat exchangers, filters, valves, hoses, and seals. Faults in them affect the entire system and lead to downtime. (Ewellix, 2021c; Tolomatic, 2021b).

Some of the components or solutions such as bleed and relief valves, incombustible fluid and automatic fire alert systems increase the safety of HLA systems in operation but make the overall system more complex. The EMLA systems without fluid under pressure are safer to operate. Safety can also be improved with an external fail safe brake. The fluid pressure is also generated by the compressor usually even when the HLA is not in motion and thus the energy consumption is continuous. EMLAs use energy only for the need and the high efficiency of converting electricity to mechanical power saves energy compared to HLA. (Ewellix, 2021c).

The linear unit of the EMLA has typically a higher weight and size due to more components compared to the corresponding HLA linear unit. This may lead to problems with EMLAs when the replacement linear unit should fit in the same length of space as HLA. Similarly, the linear units of the HLAs also have a higher power to own weight ratio. On the other hand, when comparing the overall system, the EMLA system is generally lighter than the complex HLA system and takes up less installation space due to the smaller number of additional components such as pumps, motors, hoses, valves, and filters. EMLAs require a motor, possibly a driver depending on the type of motor and power cables as additional components that require less space to operate, and the installation is simpler. (Ewellix, 2021c). Table 2 summarizes the pros and cons of EMLAs.

Table 2. *Pros and cons of EMLAs.*

Electromechanical linear actuators	
Pros	Cons
No need for regular maintenance No leaks, no environment pollution High reliability Low noise level Easy controllability High positioning precision Fewer components in system Require less installation space Low energy consumption Safe operation Energy savings Lower Total Cost of Ownership	High but lower force capacity in relative to the most competitive HLAs Large linear unit weight and size Average power to own weight ratio Length problems as HLA replacement More expensive linear unit

According to Tolomatic (2021b), by improved risk mitigation with clean technology, reduced maintenance, and efficient use of electricity, EMLAs can have a significantly lower total cost of ownership (TCO) compared to HLAs. HLA systems generally operate in the 40 to 55 % efficiency range, while EMLA systems achieve 75 to 80 % efficiency range. Efficiency affects to energy consumption and utility costs. The improved control provides process optimization and flexibility, that have a decreasing effect on the costs during the life cycle. (Tolomatic, 2021b).

Hidden costs (Figure 6), such as installation, operating costs and disposal fees are difficult to recognize but are remarkable part of the TCO. Even though the buying price of HLA is lower than of electromechanical one, hydraulic ones have more hidden costs over their life and are more expensive from the point of view of the TCO. EMLA systems perform more efficiently, with minor maintenance and have lesser negative impact to the environment, in comparison to HLA systems. On the other hand, electric servo systems can have more installation costs. (Tolomatic, 2021b).

Figure 6. *Hidden costs have a significant impact on the actuator's total cost of ownership. (Tolomatic, 2021b)*

When considering machine downtime and maintenance in terms of hidden costs, the HLA system has more serviceable components, more complex maintenance, more frequent re-lubrication, and slower replacement with a new device. EMLAs also need less spare parts and do not need safety and hazard prevention equipment and procedures that bring hidden costs to HLAs. (Ewellix, 2021c).

Ewellix (2021b) provides a cost saving calculator to estimate the operating costs of hydraulic and electromechanical technologies. The following is an illustrative example of the annual cost differences between EMLAs and HLAs. The example is indicative and not particularly reliable or valid, as it is based on the individual OEM's measurable cost views. It would also be desirable to test the application information with a number of different values to make the result more valid. Thus, the example does not give accurate results but highlights the importance of hidden costs and serves as a guide to the magnitude of the annual cost differences between HLA's and EMLA's operations. The Ewellix cost saving calculator tool is used for the example and the values entered in the tool are estimated values for a basic high force linear actuator application.

Figure 7 represents the first step of the calculation, where estimates of the application information related to the machine usage and the cost of electricity are entered. The

European reference value 0.1283 € per kWh for non-household consumers in the first semester of 2021 (Eurostat, 2021) is used in the cost of electricity. The linear actuator is used for a full 52 weeks a year and 80 hours a week and half of the operation time.

Electricity cost (kWh):	Operational weeks per year:	Hours per week full load:
€ 0.12	52	40.0
Operational time per week (Hours):	**% of time when cylinder is operating:**	**Hours per week idling:**
80	50 %	40.0

Figure 7. *Ewellix cost saving calculator: Application information (Ewellix, 2021b).*

Figure 8 shows a comparison of the annual costs of EMLA and HLA for basic high force applications. The values in the current hydraulic setup are set to the cylinder bore diameter of 100 mm, the system pressure of 180 bar and the average speed of 100 mm/s. The dynamic push force of such an application is 141 kN. The Ewellix cost saving calculator (2021b) has set estimated the HLA efficiency to 95%, the counterbalance valve efficiency to 93%, the flow control valve efficiency to 68 %, the hydraulic power unit efficiency to 67% and the overall compressor efficiency to 65%. For the EMLA, the linear actuator motor power is set to 10 kW.

Current setup: hydraulic

Is the pump/compressor working when the cylinder is idle?	No
Cylinder bore diameter (mm):	100
System pressure (bar):	180.00
Average speed (mm/s):	100
Cylinder efficiency (%):	95 %
Counterbalance valve (%):	93 %
Flow control valve (%):	68 %
Hydraulic power unit efficiency (%):	67 %
Overall compressor efficiency (%):	0.65

Annual cost comparison

Hydraulic (€):	19,463.46
Actuator stand-alone (€):	2,668.64
Saving amount (€):	16,794.82

Annual kWh cost:	
Full Load (€):	18,988.74
Idle Load (€):	474.72
Total cost (€):	19,463.46

Electromechanical replacement:

Actuator motor power (W):	10,000.00
Annual kWh cost:	
Full Load (€):	2,668.64
Total cost (€):	2,668.64

Figure 8. *Ewellix cost saving calculator: Annual cost comparison of EMLA and HLA (Ewellix, 2021b).*

As shown in Figure 8, the annual saving amount in costs by using the EMLA in this application instead of the HLA would be 16794 €. Considering that in this application the actuator achieves 2080 operating hours per year, despite the large number of operating hours, a significant difference in the TCOs between the HLA and the EMLA can be seen. The annual saving amount could still be even higher, especially if the pump or compressor would be working while the HLA is idle. If this setting is changed from no to yes, the tool will increase the idle load cost from the 475 € to 18989 €. Thus, the tool estimates the increase in the total cost to be 37977 €. Also, depending on the application, the EMLA motor power can be dropped to 5 kW, for example, which would halve the annual cost to 1,334 €. (Ewellix, 2021b).

2.4 Electromechanical linear actuator sizing and selection as replacement of hydraulic linear actuator

Replacing a HLA by an EMLA is not a simple process, as previous HLAs may be oversized. For the proper sizing of EMLA, it is important to measure or simulate the operation of the previous HLA system. Key variables, such as force and motion profile, are needed to internalize, when a HLA system is converted to a EMLA system. The first step in the replacement process is to know how much force the old HLA system has needed in its working cycle. Next, the application working cycle should be identified or evaluated for proper sizing by using a motion profile. (Tolomatic, 2021b).

The description of force and motion profile in this chapter represents their importance in the EMLA sizing process. They provide the basis for the overall sizing process when HLAs are replaced by EMLAs. Therefore, maximum dynamic force and maximum linear velocity related to these, for example, are significant performance characteristics in the comparative QFD analysis which is performed in chapter 5.

Force is a function of the hydraulic pressure in the HLA (Tolomatic, 2021b).

$$F = pA \tag{1}$$

Where:

F	Force
p	Hydraulic working pressure
A	Effective area of the HLA

When replacing a HLA by an electromechanical one, a common mistake is to use the maximum pressure of the hydraulic system in the calculation. In this case, it is assumed that the previous hydraulic system is not significantly oversized. Oversizing is common in HLAs because it does not have a significant impact on overall costs. In EMLAs, on the other hand, the cost rises greatly from oversizing. This means that the simplified calculation of the force in equation (1) could easily lead to an oversized and overpriced solution. (Tolomatic, 2021b).

Getting realistic results of hydraulic pressures from an old hydraulic system might be challenging, but it is important to measure as accurate results as possible, while the previous system is in operation (Tolomatic, 2021b). Another way is to try to simulate the operation of the application and its most typical working cycle. The working cycle can be outlined as accurately as possible in the motion profile, for better understanding of the application and allowing OEMs to size the EMLAs more accurately based on the motion profile simulation.

For example, in the Tolomatic's sizing tool (Tolomatic, 2021d), the motion profile represents an application as a cycle graph, where linear velocity is as a function of time. For the motion profile graph, the total moving distance is either entered to represent forwards or backwards motion in the velocity profile. Dwell times can be added between the velocity profiles. The final sizing also takes into account the loads or forces applied to the velocity profiles.

Figure 9 represents the motion profile in the (Tolomatic, 2021d) sizing tool. In this example of a motion profile, the travelled distance in forward motion is 500 mm, as is the distance travelled backwards. The back and forth motions last 5 seconds and there are 5 second dwell times between them. The maximum linear velocity is 125 mm/s in both directions.

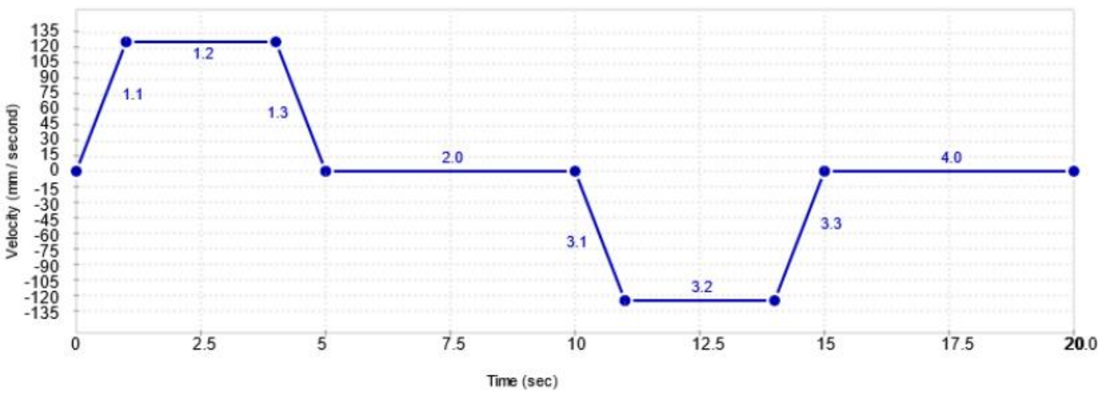


Figure 9. *A motion profile graph in the Tolomatic sizing tool (Tolomatic, 2021d).*

Based on the application information and motion profile results, the EMLA product best suited to the application can be selected. The sizing tool provides matched products from Tolomatic's product range and generates estimates of motor specifications, screw critical speed, and force capacity for the EMLA. The sizing tool also predicts the life cycle and how far the motion profile is as a percentage of the EMLA’s thermal limit. (Tolomatic, 2021d).

3. STRUCTURE AND ORIGINAL EQUIPMENT MANUFACTURERS OF ELECTROMECHANICAL LINEAR ACTUATORS

For a comprehensive understanding of the performance characteristics of EMLAs, it is important to become familiar with its structure. The most critical parts and the most common failure points of the EMLAs are screws and bearings. Their still predictable life cycles and minor need for maintenance facilitate appropriate sizing of EMLAs. (Ewellix, 2021c).

3.1 Screw

Screw is a mechanical device in an EMLA, that converts rotary torque of an electric motor into a linear motion. Ball, lead, and roller screws are typical screw types used in EMLAs. The mechanical efficiency and the lead of the screw, as well as the load and the speed capabilities, greatly affect the performance of the EMLA. (Ewellix, 2021c). Figure 10 represents examples of the most common screw types.

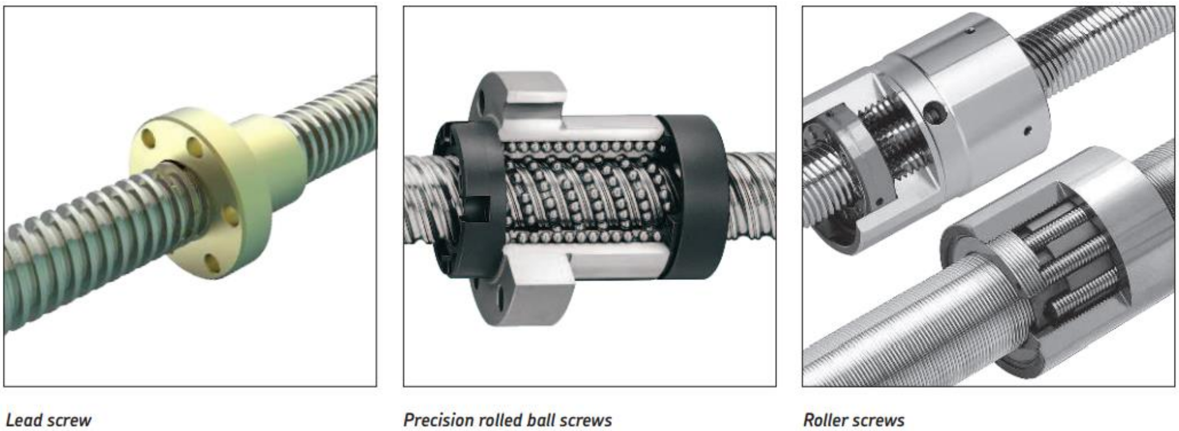


Figure 10. *Examples of the most common screw types (SKF, 2017).*

3.1.1 Screw lead

The lead of a screw is the linear distance which the screw moves in one revolution. The speed and torque of the roller screw varies with different screw leads. The longer the screw lead, the higher the linear travel velocity of the screw. (Badrinarayanan et al., 2018).

Christopher Nook (2021) describes in the blog of the OEM, Helix, that the axial load capacity and rotational speed significantly determine the performance of a screw. Pressure velocity, also known as the PV curve, is the relationship between these two factors. Safe limits for load and speed can be determined using a PV curve. The linear travel speed of the screw can be affected by changing the rotational speed and the lead of the screw. (Nook, 2021).

The rotational speed of the screw can be increased by shortening the screw lead and conversely, the rotational speed decreases as the screw lead increases longer (Nook, 2021). For the MWMs, it is typically more important for the application to withstand high loads than to have high speed capabilities, so shorter screw leads are more suitable than longer ones. Table 3 shows the advantages and disadvantages of increasing and decreasing the screw lead.

Table 3. *Pros and cons for longer and shorter screw leads (Nook, 2021).*

Increasing screw lead	
Pros	Cons
A lower motor rotational speed leaves more motor torque available. As a result, a smaller motor can be selected.	Longer screw leads are more susceptible to back drive. As a result, the need for the brake increases and the rise in the number of components increases costs.
The motor can be run closer to the optimum and the most efficient speed.	Longer screw lead has worse positioning resolution as the change in linear distance is smaller per revolution.
An inexpensive, low-complex, and fixed-speed motor without tachometer or feedback controls can be used.	A custom screw lead may be required, which increases costs and extends lead time.
Decreasing screw lead	
Pros	Cons
Shorter screw leads typically have a higher load capacity.	A higher motor rotational speed leaves less motor torque available. As a result, the size of the motor may need to be increased.
Shorter screw lead has better positioning accuracy because the change in linear distance is less per revolution.	Needs a programmable motor such as servo or mechanical components such as gears to increase speed and costs increase as a result.
Standard screw leads can be used, saving costs and lead time.	The critical speed that breaks the actuator can be reached more easily.
	If a stepper motor is used, it has a relatively low speed limit and loses torque rapidly as the speed increases. A servomotor, on the other hand, is an expensive option.

3.1.2 Comparison of screw types

According to the EMLA OEM Exlar (Shelton, 2010), controlled linear motion options include hydraulic and pneumatic linear actuators, as well as roller, ball, and lead screws in EMLAs. Roller screw typically offers many advantages in performance in relation to the other options. The efficiency of a roller screw can be over 90 percent and a ball screw is the only one option with the same level of efficiency. When comparing the life cycle, roller screw can have a few times longer life compared to ball screw. Due to high wear and friction, the life of lead screws is very short. (Creative Motion Control, 2021d; Shelton, 2010).

The high-quality performance of the roller screw comes from its structure for force transmission. Around a threaded rod in the roller screw system, threaded rollers are assembled in a planetary configuration. By that design, rotary motion of an electric motor is converted into linear displacement. Radiused flanks in the rollers provide plethora of contact points. (Shelton, 2010).

Roller screws are ideal for demanding and continuous applications because they can cycle more frequently and turn faster than ball and lead screws. With the numerous contact points, roller screws have high load capacities, long functional life, and low amount of stress within the system, leading to an improved stiffness. For example, the ball size limits the number of contact points in a ball screw system. Due to the rigid design and high load capacity, roller screw cylinder has typically lower space requirements than other options. Roller screw technology is often more expensive than other screw types, but in the long run the costs are reimbursed with a long life cycle and low need of maintenance. (Creative Motion Control, 2021d; Shelton, 2010; Tolomatic, 2017).

On the other hand, the high performance of the EMLAs of Motiomax has shown that a ball screw can also be a very effective solution. The efficiency of their ball screw reaches up to 95 %. (Motiomax, 2021). For MWMs, however, the selections of the best-performing EMLAs are made not only on the basis of the type of screw, but also on the basis of the properties and performance characteristics obtained from them.

As represented in the chapter 5, different OEMs give distinct results on the performance of roller and ball screws, so certain ball screws may offer even preferable performance compared to certain roller screws. It is typically thought that roller screws have enhanced force properties over size, but the empirical research during the thesis has shown that the greatest differences in force characteristics are between OEMs rather than screw types. Table 4 shows a general perspective between the different controlled linear motion options.

Table 4. *Comparison of linear motion options of linear actuators (Shelton, 2010).*

	Roller screw	Lead screw	Ball screw	Hydraulic linear actuator	Pneumatic linear actuator
Load capacity	Very high	High	High	Very high	High
Life cycle	Very long	Very low	Mediocre	Long with proper maintenance	Long with proper maintenance
Velocity	Very high	Low	Very high	Mediocre	Very high
Acceleration	Very high	Low	Mediocre	Very high	Very high
Electric positioning	Simple	Mediocre	Simple	Complex	Very complex
Stiffness	Very high	Very high	Mediocre	Very high	Very low
Space requirements	Minimum	Mediocre	Mediocre	High	High
Efficiency	> 80 %	~ 40 %	> 90 %	< 50 %	< 50 %
Maintenance	Very low	High	Mediocre	Very high	High
Environmental	Minimal	Minimal	Minimal	Hydraulic fluid leaks and disposal	High noise levels

3.2 Rolling bearings

A bearing is a device that supports high loads and allows small frictional movement between two surfaces loaded against each other (Ewellix, 2021c). Rolling bearings support and guide the rotating or oscillating machine components with minimal friction and transfers the load between the machine parts. The cost-effective rolling bearings are characterized by high precision and minimal friction, reducing wear, energy consumption, heat, and noise, while allowing high rotational speeds. (SKF, 2021).

Rolling bearings have two basic types: ball bearing and roller bearing. Ball bearings use balls as rolling elements between the inner and outer rings and roller bearings use rollers. Balls and rollers are shown in Figure 12. Rolling bearings can also be classified into radial and thrust bearings based on the direction of the supported load. (SKF, 2021).

EMLAs are typically equipped with thrust bearings that support forces acting primarily in the direction of the axis of the shaft. In radial bearings, the forces act in the opposite direction, i.e., perpendicular to the axis of the shaft. Thrust bearings can support either axial loads only or also radial forces depending on the design. Radial bearings are also able to support higher speeds than thrust bearings of the same size. The contact angle determines whether the bearing is of the radial or thrust type. If the contact angle is ≤ 45° from the axial center axis, the bearing is radial and with the contact angle of > 45° the bearing is the thrust type. (SKF, 2021).

Figure 11 represents rolling bearings from right to left as follows: radial roller bearing supporting only radial loads, radial ball bearing supporting both radial and axial loads, and thrust roller bearing which supports axial and radial loads. The axial center axis is visible vertically in the center of the rightmost bearing.

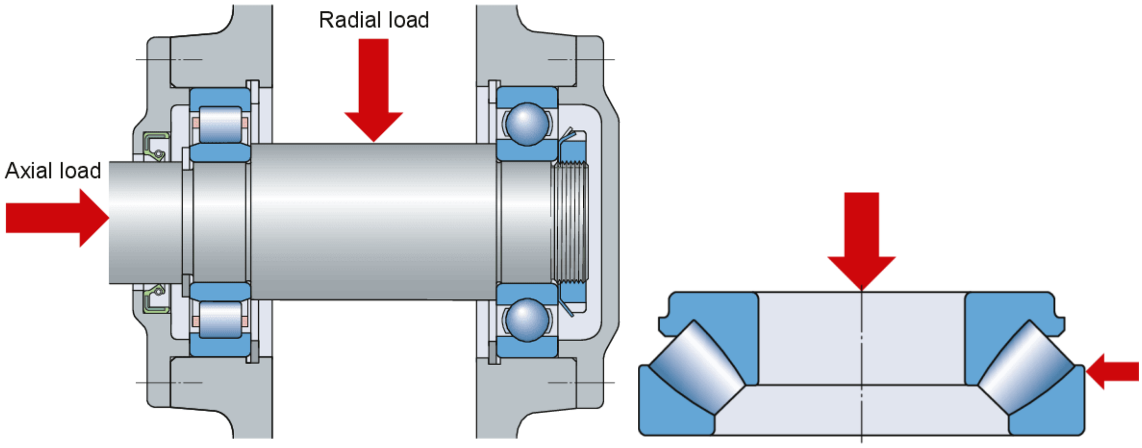


Figure 11. *Rolling bearings from left to right: radial roller bearing supporting only radial loads, radial ball bearing supporting both radial and axial loads, and thrust roller bearing which supports axial and radial loads. (SKF, 2021).*

Ball and roller bearings differ in the way they are in contact with the ring raceways. As Figure 12 represents, the balls are in point contact and the rollers are in line contact with the raceway. As the act of the force increases on the bearing, the contact point of the ball bearing becomes an elliptical area and the contact line of the roller bearing becomes a rectangular area. The smaller elliptical contact area of the ball bearing produces low rolling friction and the larger rectangular contact surface of the roller bearing produces high rolling friction. Therefore, the roller bearings are able to support higher forces but lower speeds, while the force supported by ball bearings is limited but allows higher speeds. (SKF, 2021).

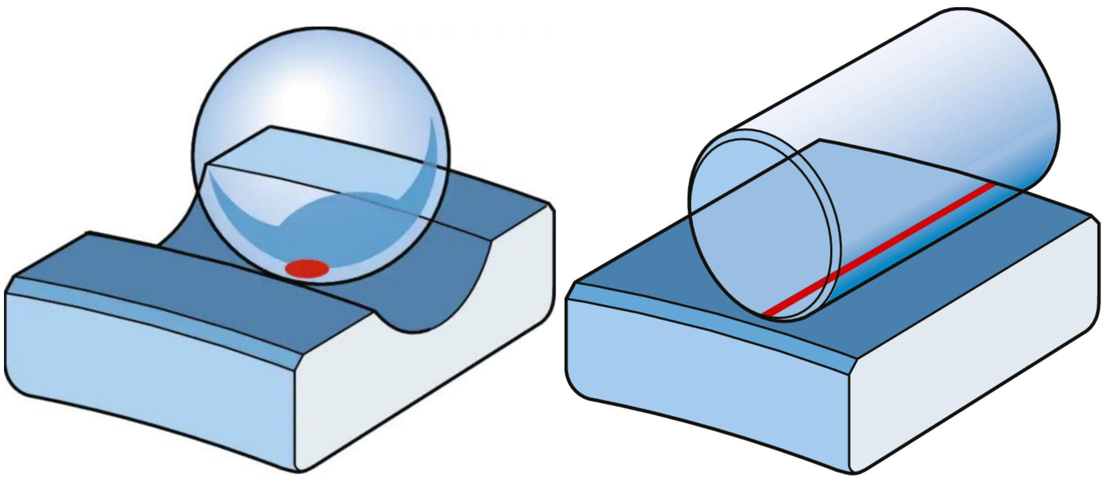


Figure 12. *The balls make point contact, and the rollers make line contact with the ring raceways. (SKF, 2021).*

In addition to the screw, the bearings are the most common failure points, so the performance of the bearing has a significant effect on the life cycle. In the high performance

EMLA context, the bearings are typically located at the rear of the linear unit and supporting the screw shaft. (Ewellix, 2021c).

Based on the public catalogs of the high-force EMLA OEMs, Ewellix (2021c) and Tolomatic (2021c) use angular contact ball bearings in their EMLAs, while Creative Motion Control (2021c) uses grooved roller bearings to support the screw shaft from high forces. In the SKF angular contact ball bearings used by Ewellix, there are ring raceways in the outer and inner rings that are offset from each other in parallel to the bearing axis. (Ewellix, 2021c). The Creative Motion Control's patented grooved roller bearing has a high load capacity due to the increased number of contact surfaces in the grooved roller design. (Creative Motion Control, 2021c).

3.3 Mounting configurations

There are a variety of mounting options for EMLAs at both ends. Frequently available rear mounting options are front flange, plate, rear clevis, rear eye, and trunnion attachments. In the front end, rod end configurations include clevis, eye rod end and threaded rod. Mountings can be selected by utilizing the previous HLA structure and by surveying the possible ranges of movement of the preceding HLA. Figure 13 shows Creative Motion Control’s eye and clevis attachments which provide possibility to wide range of motion angles. (Creative Motion Control, 2021b; Ewellix, 2021c; Tolomatic, 2021c).

Figure 13. *Mounting options for Creative Motion Control CPD EMLAs. Top left: clevis rod end, top right: rear clevis, bottom left: eye rod end, bottom right: rear eye (Creative Motion Control, 2021b).*

3.4 Brake

For safety reasons, it is important to enable the actuator to remain stationary, for example during a power failure. Mechanical brakes are the solution to this problem. EMLAs usually need to be integrated to either an electrical or mechanical brake. In general, brake is especially required for high efficiency EMLAs with high screw lead and gear ratio combined. The EMLA can also be self-locking, so it does not need a brake to lock during a power failure. Such actuators have typically low efficiency and do not backdrive while reaching a standstill. (Linak, 2021b).

When designing the EMLA, it is advisable to choose the location of the brake carefully. For example, the further the brake is from screw, the less force is needed for braking. Placing the brake close to the electric motor of the EMLA reduces the end play required for the brake activation. (Linak, 2021b).

3.5 Original equipment manufacturers and their high performance electromechanical linear actuator products

There are not many OEMs that are able to meet the requirements of current HLAs in MWMs. Creative Motion Control, Ewellix, Motiomax, Royal Cylinders and Tolomatic manufacture EMLAs that achieve high dynamic forces and can operate in harsh environment. The most competitive products of these OEMs are considered in the comparative QFD analysis in chapter 5.

3.5.1 Creative Motion Control

Creative Motion Control is an American OEM of linear motion control products. The 2002 founded company supplies EMLAs, roller screws and grooved roller bearings and is located in Woodinville, Washington. The products have been described to perform with high load capacity, high efficiency, and long life. (Creative Motion Control, 2021a)

Figure 14 represents a detailed view of the Creative Motion Control's CPD series EMLA and its main components. The Creative Motion Control’s internal planetary gearbox enables different options for the optimal combination of load, speed and required torque for a variety of applications. (Creative Motion Control, 2021b).

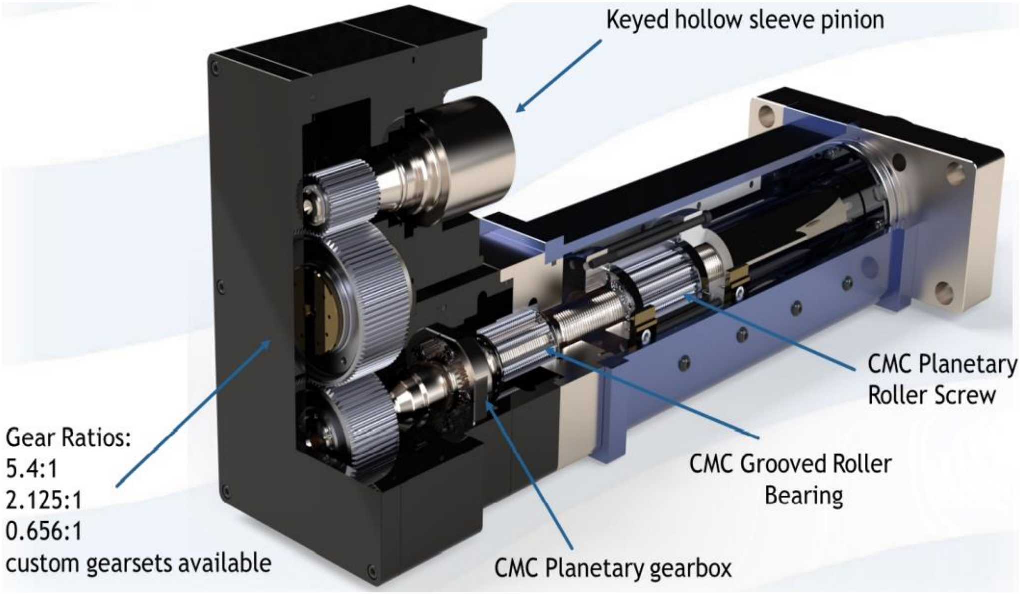


Figure 14. *Creative Motion Control CPD series EMLA structure and main components (Creative Motion Control, 2021b).*

Figure 15 shows the Creative Motion Control’s planetary roller screw and grooved roller thrust bearing on the screw shaft. Creative Motion Control’s patented grooved roller bearing technology plays a key role in allowing high continuous dynamic forces, high speeds, and a long life cycle. It is compatible with the roller screw’s load capacity and life cycle. (Creative Motion Control, 2021b).

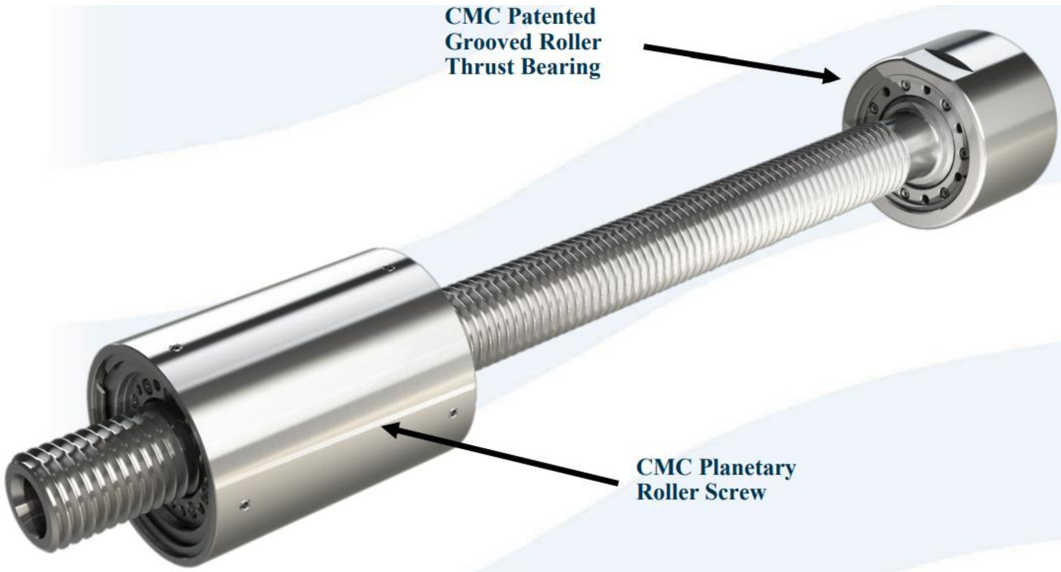


Figure 15. *Creative Motion Control’s planetary roller screw and grooved roller bearing on the screw shaft (Creative Motion Control, 2021b).*

Figure 16 represents a more detailed view of the parts of the planetary roller screw. The numbering gives additional information about the structure of the roller screw. Roller nut

(1.) and the screw shaft both have a threaded surface with straight flanks and multi-start threads. The rollers (2.) have single start threads with a modified thread profile as well as a spur gear and a cylindrical journal at both ends. The ring gear (4.) matches the rollers at both ends, keeping them parallel and preventing the rollers from skewing. The ring gears (4.) are secured in place with pins (3.) and timed during assembly. The roller axles coincide with a spacer (5.) which rotates and is held in place in the nut by a retaining ring (6.). (Creative Motion Control, 2021d).

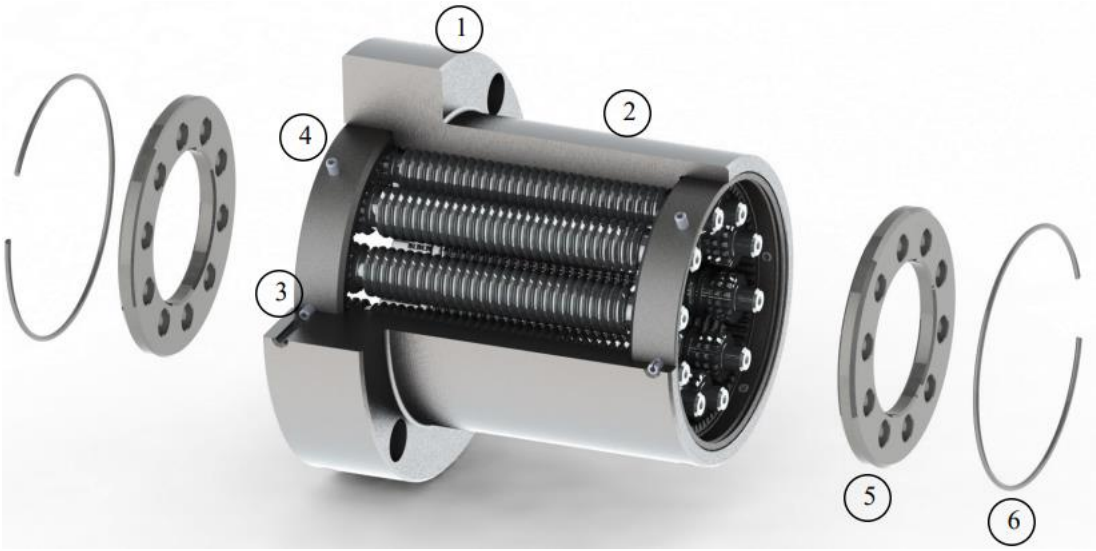


Figure 16. *A more detailed view of the parts of the planetary roller screw of Creative Motion Control (Creative Motion Control, 2021d).*

Planetary roller screws of Creative Motion Control exploit threaded rollers as rolling elements, which means that the contact surface of the load transfer is considerably larger than, for example, in ball screws where the rolling elements are bearing balls. In particular, threaded rollers increase the load capacity and the life cycle of the roller screw. (Creative Motion Control, 2021d).

Figure 17 represents a more detailed view of the grooved roller thrust bearing. The numbering introduces the five primary components of the grooved roller bearing. The grooved inner race (1.), grooved outer race (2.), and grooved rollers (3.) carry the load. The spacer (4.) positions and holds the rollers (3.) in place. The spacer (4.) is held in place by the retaining ring (5.). (Creative Motion Control, 2021c).

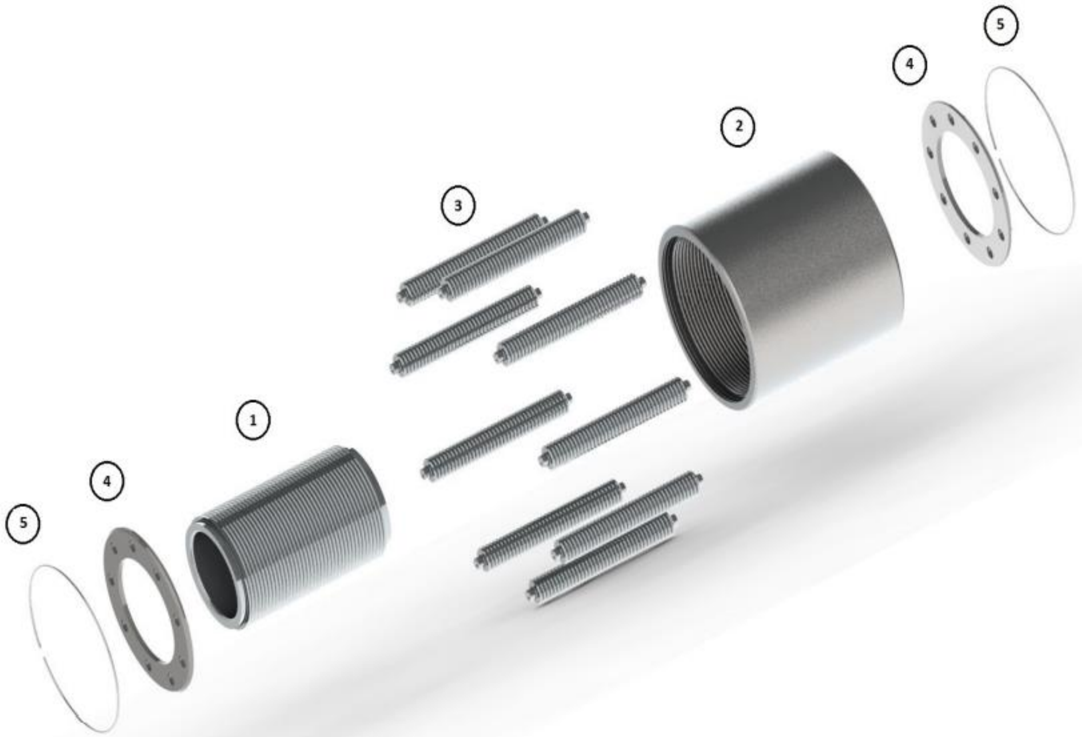


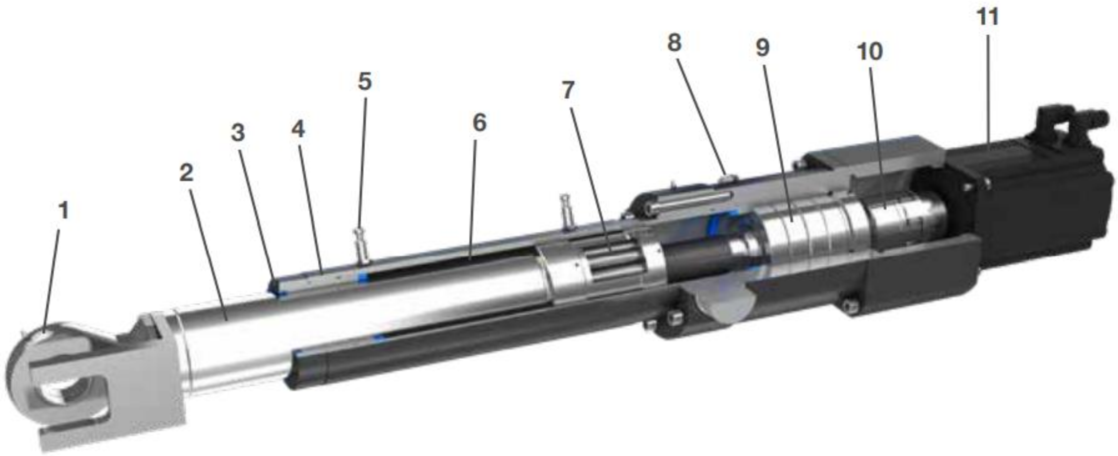
Figure 17. *A more detailed view of the parts of the grooved roller bearing (Creative Motion Control, 2021c).*

The patent projected grooved roller bearing is competitive and effective compared to other similarly sized bearings thanks to the grooved design. The grooved design technology is simply based on a larger number of contact surfaces in the same size space. According to (Creative Motion Control, 2021c), the total cost of ownership is better than any competing bearing on the market. Especially maintenance and replacement costs are significantly lower, alongside the total costs. (Creative Motion Control, 2021c).

3.5.2 Ewellix

Ewellix is a global supplier of linear motion components and actuation applications. They design and manufacture EMLAs, control units and operating devices and ball and roller screws, that are used in industrial automation, automotive assembly, mobile machinery, and medical applications. The company is owned by Triton and headquartered in Gothenburg, Sweden. Ewellix employs 1200 workers and has 16 sales units and 8 factories. The company was formerly part of the SKF Group. (Ewellix, 2021a, 2021d).

The high load capacities of Ewellix's SRSA product are, among all model options, the most competitive for the application. Other options such as SVSA and SLSA are available for better positioning accuracy and higher linear velocity but with lower load capacities. According to Ewellix, the SRSA product has many typical advantages associated with actuator electrification, such as minor maintenance requirements, minimal environmental influence, and long life cycle. (Ewellix, 2021c). Figure 18 represents the structure of the Ewellix SRSA inline configuration product.



1. Rod end
2. Steel push tube
3. Scraper seal to protect against contaminants
4. Guiding bushing
5. Home and limit switches
6. Steel protection tube
7. High quality Ewellix planetary roller screw for highest axial loads with low play and high efficiency
8. Sinter filter for high airflow
9. High quality SKF angular contact ball bearings
10. Coupling
11. Servomotor

Figure 18. *Ewellix SRSA EMLA inline configuration structure (Ewellix, 2021c).*

The numbering in figure 18 for the EMLA provides more information on the structure of the SRSA product. The SRSA product is equipped with high performance planetary roller screws and servo motors that offer highly efficient movements and full controllability. The actuator can be ordered with Lenze servo motors and drives selected by Ewellix but can also be combined with a motor of an optional OEM. A very stiff and robust structure is achieved by the steel housing. SKF's angular contact ball bearings provide holding capability for high loads and the guiding bushing reduces friction between moving parts. Figure 18 shows an inline structure, but the parallel configuration required for the QFD analysis in chapter 5 is also available. (Ewellix, 2021c).

3.5.3 Motiomax

Motiomax is a Finnish company, which supplies overall electromechanical solutions for the need of linear and rotational motion in demanding applications. The solutions are energy-efficient, optimized for the customer and almost oil-free. Their product portfolio includes EMLAs, electric motors and automation solutions. Motiomax's motion systems with appropriate connectivity, support automation industry and the electrification of heavy-duty MWMs. (Motiomax, 2021)

Motiomax offers the largest dynamic maximum forces on the EMLA market up to 2000 kN. Their EMLAs have low noise levels, high mechanical efficiency and they provide precise and easy-to-control motions. Motiomax's EMLAs differ from the other high force EMLAs on the market by using a ball screw instead of a roller screw to implement linear movements. Motiomax's majority owner and its partner in implementing motion solutions is Norrhydro, which manufactures energy-efficient HLAs and is planning to be listed on the Helsinki Stock Exchange's First North marketplace. (Motiomax, 2021).

Because the Motiomax’s EMLA products are customer-specific, there is no public catalog offered which would provide the specifications needed for the QFD comparison analysis in chapter 5. As a result, Motiomax is excluded from the QFD analysis, while acknowledging that they offer by far the best dynamic and static maximum forces on the EMLA market. Figure 19 shows two different EMLA solutions from Motiomax.

Figure 19. *Motiomax EMLAs (Motiomax, 2021).*

3.5.4 Royal Cylinders

The electromechanical, pneumatic, and hydraulic linear actuators of the United States based Royal Cylinders brand are manufactured by Westcoast Cylinders Inc. Royal Cylinders focuses on producing dependable and easy to maintain actuators with long life cycle. The company's headquarters is located in New Westminster, Canada. (Royal Cylinders, 2021a).

Figure 20 represents the all-steel construction structure and features of the Royal Cylinders E-Series EMLA. The precision planetary roller screw and the grooved roller bearing enable high forces up to 311 kN and a long life cycle. The figure also provides a detailed view of small parts such as seals, scrapers, bumpers, and wear strips. Seals and scrapers protect the internals from contaminants and damage. The other mentioned parts extend the life cycle, as the wear strips eliminate wear, and the bumpers reduce impacts to the internal components. At the rear end, a torque transmission timing belt can be seen in the parallel motor mounting structure. (Royal Cylinders, 2021b).

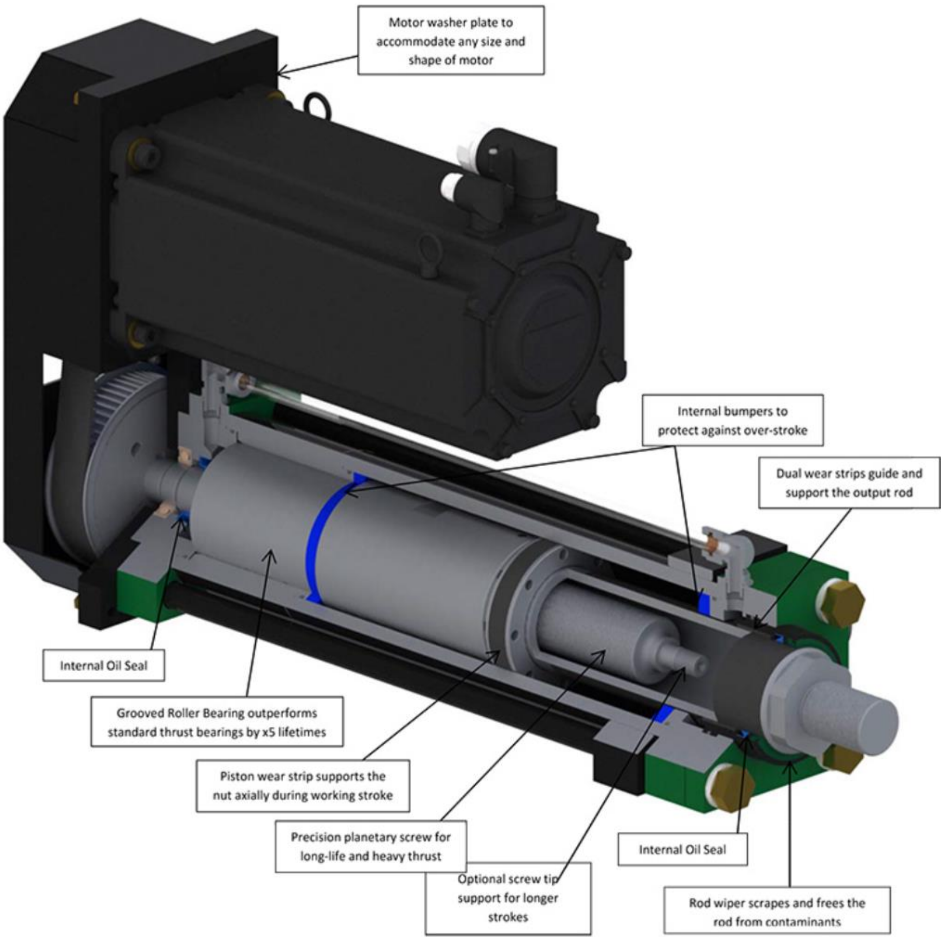


Figure 20. Royal Cylinders E-series EMLA mechanical structure (Royal Cylinders, 2021b).

3.5.5 Tolomatic

Tolomatic is a United States based company, headquartered in Hamel, Minnesota. The company designs, manufactures and markets automation components in electric linear motion, pneumatic and power transmission technologies. (Tolomatic, 2021a).

RSX extreme force, hydraulic quality actuators provide the highest forces available from Tolomatic. The RSX EMLAs are rod-style and exploit planetary roller screws, allowing a long life cycle and continuous operation. Tolomatic's Your Motor Here program enables many different servomotors and gearboxes on the market to be easily mounted to an RSX actuator. (Tolomatic, 2021c).

Figure 21 represents the structure and characteristics of the RSX product. High load capacity is achieved by precision ground planetary roller screw and supported with steel thrust tube and four ball bearings. Parallel configuration option that is suitable for the QFD analysis in chapter 5, reduces the total length and includes a 1:1 or 2:1 ratio belt reduction drive. The RSX EMLAs have standard IP65 and optional IP67 class protection. (Tolomatic, 2021c).

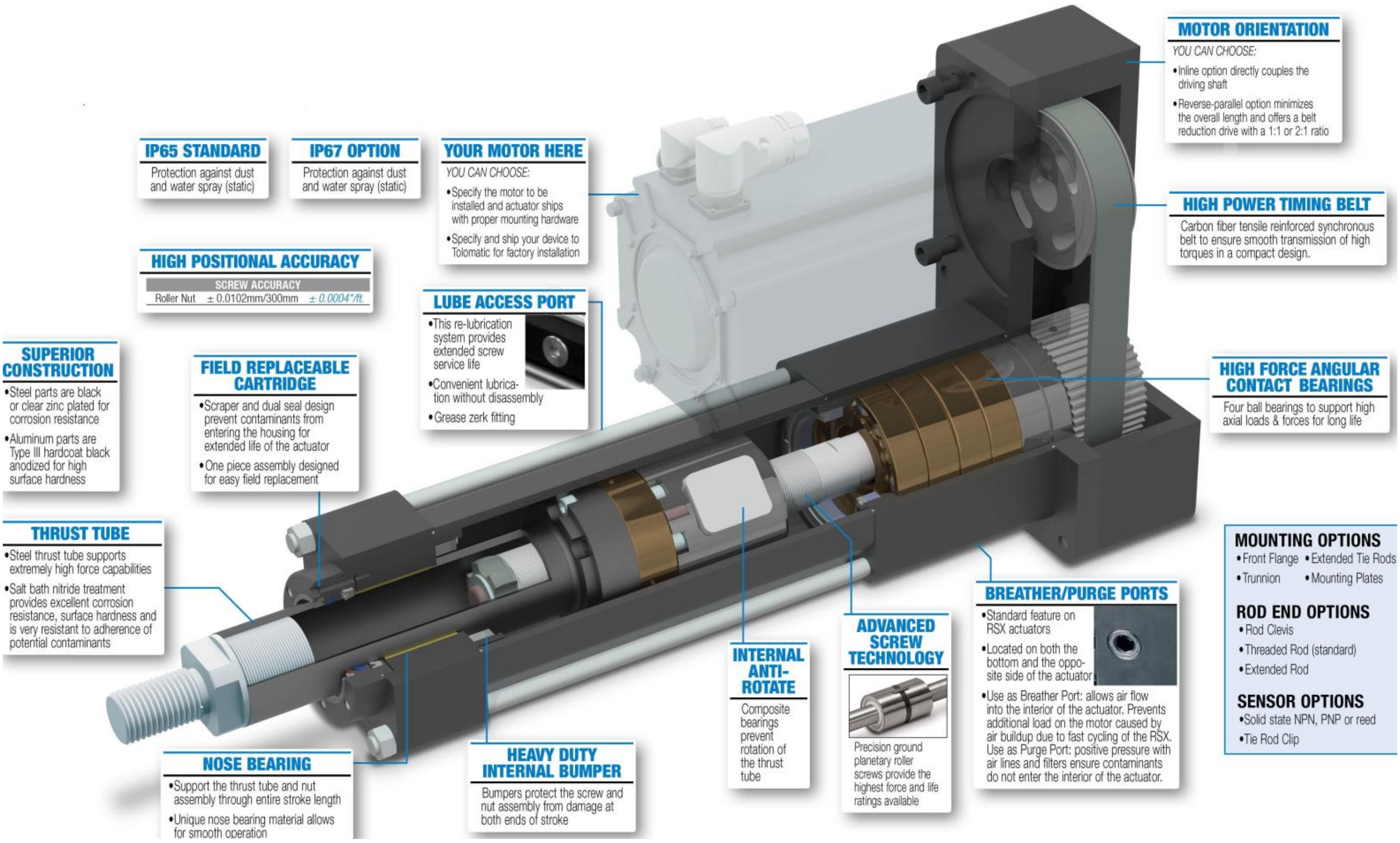


Figure 21. *Tolomatic RSX EMLA mechanical structure (Tolomatic, 2021c).*

4. QUALITY FUNCTION DEPLOYMENT, PERFORMANCE CHARACTERISTICS AND REQUIREMENTS AS INDICATORS OF COMPETITIVENESS

Quality Function Deployment (QFD) is used as a method of analysis to properly compare the most competitive EMLAs on the market. The basics of the QFD analysis is presented in chapter 4.1 and it is implemented in chapter 5.3. The QFD analysis in this thesis is based on the performance characteristics of the EMLAs which affect the result in terms of their magnitude and the level of importance. The performance characteristics are presented in chapter 4.2. Estimated limits are set for each performance characteristic to determine how an EMLA can succeed as a producer of linear motion in the estimated average MWM. These estimated limits are called requirements in this thesis. Together with the determination of the requirements in chapter 4.3, the importance levels of performance characteristics are defined.

During the QFD analysis of this thesis, the ratings are formulated for each performance characteristic based on the magnitude of the value of the performance characteristic in relative to the values of the other comparable products. The ratings are multiplied by the importance level of the performance characteristic to obtain the weighted rating which is summed up for each performance characteristic to achieve the result of the competitiveness of the product.

4.1 Quality Function Deployment analysis

Determining of how customer defines quality is one of the first and the most important steps on a typical project. After surveying the customer sufficiently, the expectations and recommendations are analysed by the Japan-originated planning process, called quality function deployment (QFD). QFD is typically utilized to gather the voice of the customer (VOC) and transforming that to customer requirements in product development. It ensures that the VOC is combined into the product design and production phases. (Cudney & Elrod, 2011; Madu, 2020). In this thesis, the customer requirements are called performance characteristics because the designation is better suited to describe the specifications and the features of an EMLA.

QFD has several benefits for companies that implement it carefully and properly. The product can be launched on the market faster, at lower operational cost and with higher quality. In other words, the objective of QFD is high-quality designing that increases profit levels, enhances customer satisfaction, and lowers the time of development as productivity increases. QFD also aims to prioritize the most significant and preferred performance characteristics and design features and select them for a more thorough attention on the further process. The tool provides systematic approach to bring customer recommendations in product design process and is commonly used in the areas of customer needs analysis, engineering, product design, quality management and product development. Understanding the VOC correctly from a product is critical to the productive design and maximized performance. (Cudney & Elrod, 2011; Madu, 2020).

The process of listening to the VOC involves the recognition of the customer's needs and integrating them into the design and production of the product. The first step is to internalize the basic customer needs. They can be collected by utilizing experimental techniques such as surveys and focus groups. Next, product design is expanded beyond the customer's basic needs and attempts are made to find needs for features that the customer is unaware to require. Proper consideration of the VOC typically leads to greater customer satisfaction in the end result. (Madu, 2020). The VOC is converted to the performance characteristics. For example, if the VOC seeks to ensure that the MWM has high safety and standard ratings, the performance characteristic for that can be defined to be safety (Cudney & Elrod, 2011).

A set of tables can be used by the QFD tool to support decision making in the engineering design process. House of Quality (HOQ) is a complex matrix, which organizes information and enhances the quality focus on the organization. HOQ is a plan for product development that utilizes the most critical customer requirements or in this thesis, performance characteristics. HOQ transforms the performance characteristics, into the weighted results of QFD analysis for each product. (Cudney & Elrod, 2011; Madu, 2020).

HOQ can be formed in many distinct ways and either simply or in a complex way. In most cases, HOQ does not compare products with each other as in this thesis, but for example the correlation and relationship between the product's customer requirements and design requirements. Customer requirements indicate what the requirement is from the customer's perspective and design requirements how the requirement is met or at what value. Thus, the complex path can include correlation tables, relationship matrix, and other components. The relationship matrix helps to recognize the customer requirements and prioritizes them by importance levels. Negative correlations between two requirements can signal conflict when attempting to achieve to meet both requirements. In this case, the requirement with the highest importance level can be selected to be fulfilled. (Cudney & Elrod, 2011; Madu, 2020). Figure 22 represents a complex HOQ template that differs from the QFD analysis implemented in this thesis. This template compares customer and design requirements and includes relationship and correlation matrices.

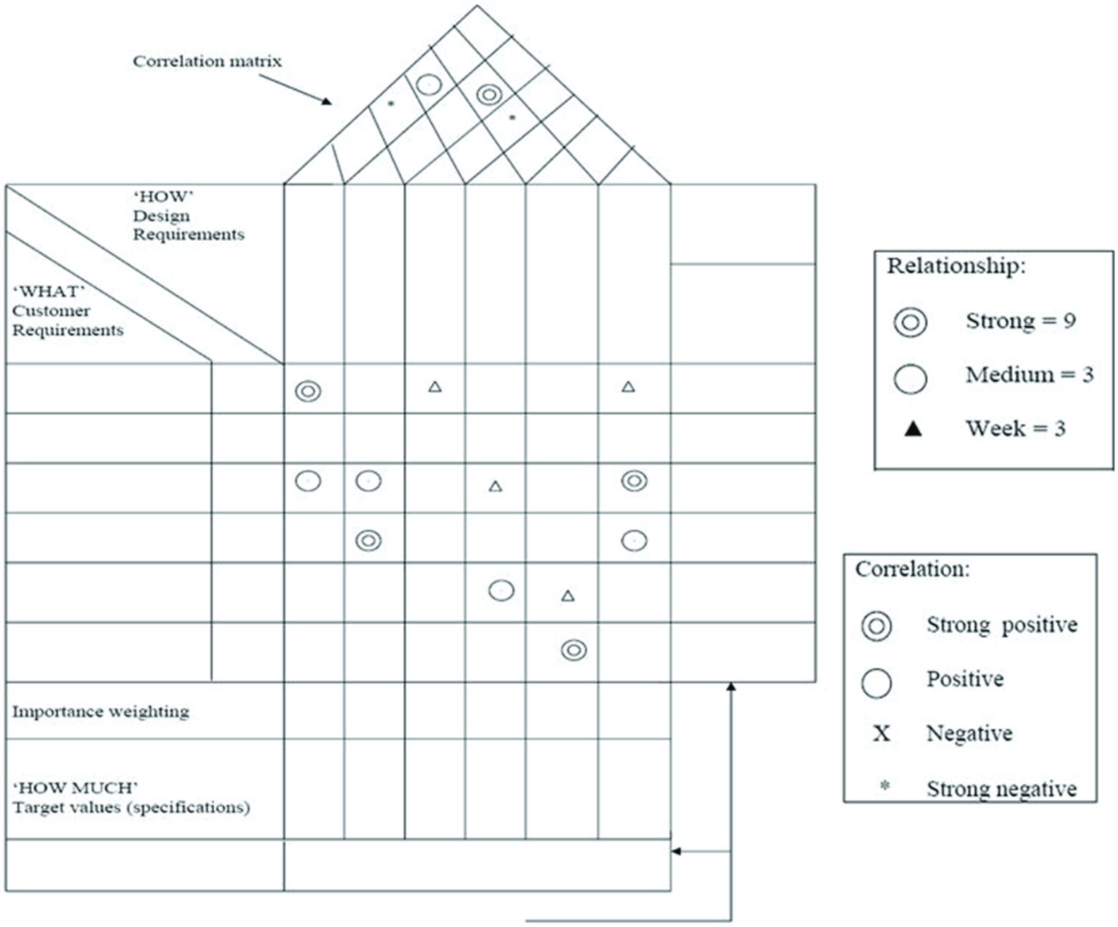


Figure 22. *A complex HOQ template with correlation and relationship matrices (Madu, 2020).*

In this thesis, a simple and modified form of the HOQ has been chosen for the weighted EMLA comparison and it is referred to as the QFD analysis hereafter. The QFD analysis of this thesis investigates how well the comparable products perform on critical performance characteristics. Thus, it can be expressed that QFD analysis is integrated with product benchmarking. The first step of the QFD analysis is the identification of the critical performance characteristics based on the VOC. In the second step, the requirements are defined for the performance characteristics and the level of importance is determined for those numerically, based on the customer's perspective. The limited requirements do not affect the QFD analysis but facilitate the establishment of importance levels. Next, the ratings are formed from the value of that performance characteristic and dividing it by the sum of the same value of it and other products. Thus, the rating is the relative share of the value of the same performance characteristic of the products. The weighted ratings are formulated from the multiplication of weights and ratings. The weighted ratings of every performance characteristics are summed together to provide the relative results of product competitiveness. (Cudney & Elrod, 2011).

From a critical perspective, proper traceability of customer requirements is important. In order to achieve more reliable results from the QFD analysis and to determine the correct importance level, the executor is typically the company's technical and engineering personnel. The process utilizes strategic objectives of product development to assure customer satisfaction. Utilizing a cross-functional team to implement QFD will improve its results, as team members have different backgrounds and bring a more holistic picture of the problem. For example, sales, marketing, and distribution departments can be more in touch with customers than engineers and can better interpret the customer requirements. (Al-Mashari et al., 2005; Cudney & Elrod, 2011; Madu, 2020). Thus, evaluation is challenging by one person and the end result would be more valid through a broader implementation by a larger group of experts.

It is possible that the values of the specifications collected from the OEM’s public catalogs may contain incorrect information due to human errors or recent changes in the OEM's technology. In addition, reliability is affected by differences in the way OEMs report some specifications. The structures of the EMLAs differ, so the lengths, heights and widths and the way they are reported vary, but not significantly. Weights may be reported differently depending on the OEM, and for example, the weights of Creative Motion Control products with a stroke length of 0 mm will need to be estimated based on increments on weights on stroke lengths in every 100 mm. The weight of the Royal Cylinders E50 EMLA also needs to be evaluated. On the other hand, weight accounts for 1/11 of the overall importance level, so its impact on the outcome is slight. Price would also be a high priority requirement and would improve the results of the QFD analysis, but price information rarely publicly available from OEMs.

4.2 Performance characteristics of electromechanical actuators

Performance characteristics describe the competitiveness of an EMLA in a particular specification or feature, typically numerically. They provide the basis for the requirements and comparative QFD analysis implemented in chapter 5.

4.2.1 Maximum dynamic force

The maximum dynamic force, F_{dyn}, in kilonewtons (kN) is the peak axial load that an EMLA can push in motion for a moment, usually at low velocity, without mechanical breakage or overheating. The maximum dynamic retraction force is often the same depending on the OEM, but it can also be different or usually less than the pushing force. The continuous force of an EMLA is also often mentioned in catalogs, which is the load that the EMLA is able to push continuously without overheating. (Ewellix, 2021c).

4.2.2 Maximum static force

The maximum static force, F_{stat}, in kilonewtons (kN) is the maximum axial load that the EMLA can push at standstill, without mechanical breakage or overheating. The maximum retraction force is often the same depending on the OEM, but it can also be different or usually less than the pushing force. (Ewellix, 2021c).

4.2.3 Dynamic load capacity

Dynamic load capacity, *C*, is a theoretical constant which is utilized to calculate the life cycle of a roller or a ball screw. The magnitude of the dynamic load capacity describes the load that with 90 percent reliability of identical ball or roller screw units can reach a life cycle of one million revolutions. (Ewellix, 2021c). Most EMLA OEMs provide a value for the dynamic load capacity in kilonewtons. Dynamic load capacity is utilized in the L_{10} life cycle calculation and therefore is not selected for the performance characteristics of the QFD analysis in chapter 5.

4.2.4 Maximum linear velocity

The maximum linear velocity, v_{max}, of an EMLA is the speed that can be achieved without breaking the mechanical system. The linear velocity is the displacement as a function of time and its unit is millimeters per second (mm/s) in this thesis. If the electric motor of the EMLA is able to rotate faster than the maximum linear velocity of the EMLA, then the speed of the electric motor must be limited. The type and the lead of the screw significantly affect the maximum linear velocity. (Ewellix, 2021c).

4.2.5 Mechanical efficiency and energy savings

Mechanical efficiency, η, of an EMLA's screw is the ratio of output power in relation to input power. Mechanical efficiency varies depending on the type of screw and the OEM. For EMLAs, the value of mechanical efficiency is typically at least 80 percent. (Ewellix, 2021c).

As Figure 23 shows, air compressibility and pressure losses make pneumatic systems less efficient than the other alternatives. The losses in the hydraulic systems arise from the conversion between pressure generation and linear motion. The compressor usually must create pressure also when there is no movement. EMLA systems do not consume energy without operation, as they use energy through demand. There is also a high efficiency in converting electricity to mechanical energy. (Ewellix, 2021c).

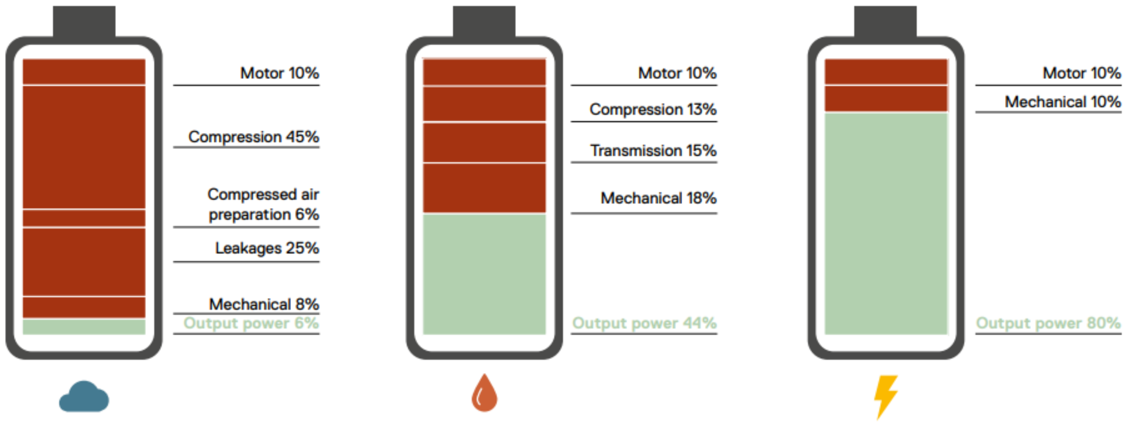


Figure 23. *Energy losses comparison. From left to right, a pneumatic, a hydraulic, and an electromechanical system. (Ewellix, 2021c)*

4.2.6 Weight

The weight, m_0, of an EMLA is usually provided with a stroke length of 0 mm in the OEM catalogs and the weight amount is increased, for example, in every 100 mm. Kilograms (kg) are used as the unit of weight. The OEMs under review state the weight in their own way, which makes the comparison difficult. One OEM may include an inline or parallel configuration to the weight, while the other may only include a linear unit in the value of weight. The linear unit of an EMLA typically weighs more than the linear unit of a HLA while the entire HLA fluid power system generally weighs more than a less complex EMLA system (Ewellix, 2021c; Tolomatic, 2021b).

4.2.7 Dimensions of height, width and length

The QFD analysis in chapter 5 considers the maximum dimensions in height, h_{max}, width, w_{max}, and length, l, given in the EMLA OEM catalogs. Figure 24 represents the dimensional drawing of the Ewellix SRSA-S-75xx EMLA with a parallel configuration. The dimensions are given in millimeters (mm) and are calculated for each OEM in the same manner as in the example below.

For example, the length value of the Ewellix SRSA-S-75xx EMLA in Figure 24, used in the comparison is obtained by summing the length dimensions 130 mm, 334 mm, and 309 mm of the dimensional drawing of Figure 24, without taking into account the stroke length. The width dimension is taken from the widest part of the EMLA system, and the value is 280 mm with the Ewellix SRSA-S-75xx. The value for the height is obtained from the height of the parallel configuration, i.e., the highest part of the EMLA, which is 640 mm high with the SRSA-S-75xx.

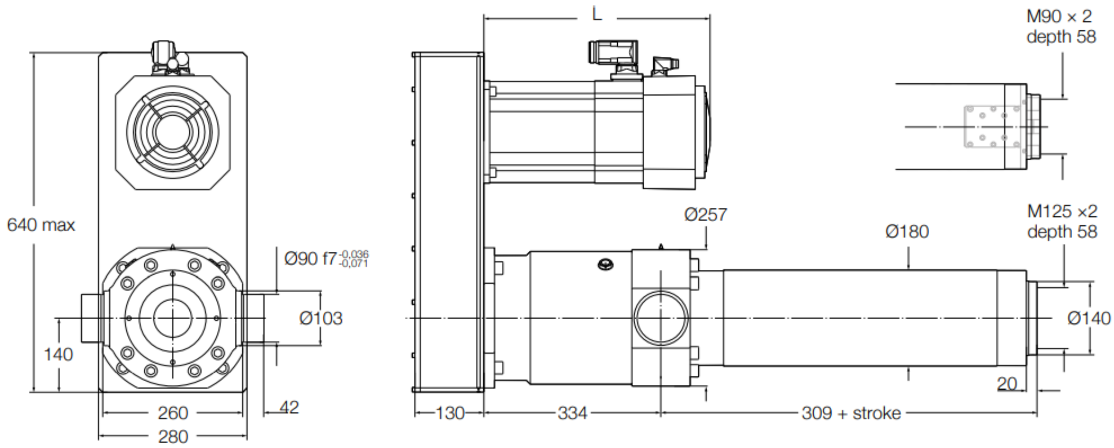


Figure 24. *Dimensional drawing of the Ewellix SRSA-S-75xx EMLA (Ewellix, 2021c).*

4.2.8 Maximum stroke length

Maximum stroke length, s_{max}, is the mechanical limit of linear distance that the EMLA can extend or retract in millimeters (Ewellix, 2021c). Figure 25 shows how the maximum stroke length is especially limited by the risk of buckling. The maximum load of the Tolomatic's RSX096 EMLA starts to decrease at a stroke length of 770 mm and the maximum load of the RSX080 EMLA decreases onwards from a stroke length of 650 mm.

(Tolomatic, 2021c). The maximum stroke length can also be affected by the linear velocity that oscillates the screw inside as well as the limitations in the manufacturing process or in the design (Ewellix, 2021c).

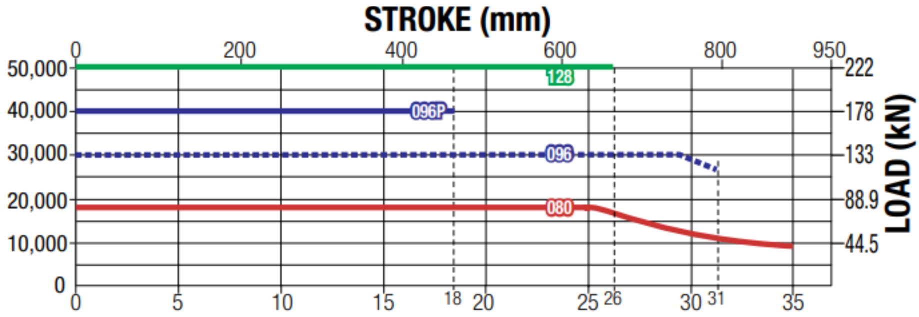


Figure 25. *Tolomatic RSX EMLA screw buckling load at different stroke lengths (Tolomatic, 2021c).*

4.2.9 Ingress Protection rating

An EMLA in a MWM should be capable to operate in harsh environment, where the equipment is intruded temporarily by dust and water. The recommended ingress protection rating for the QFD analysis in chapter 5 is IP67. Number 6 in IP67 class means that there is no ingress of dust and number 7 that protection withstands momentary immersion to water. The highest possible protection class is IP69. The ingress protection (IP) ratings are developed by the IEC and are grading the resistance of a housing against the exposure of dust or liquids. The IP codes are defined in the standard IEC 60529. There is determination of the tests to be performed for the verification that the housing meets the requirements. (IEC, 2021).

4.2.10 Operating temperature range

The operating temperature range, *T*, describes the temperature limits in the surrounding environment in which an EMLA can operate. Among other things, the ambient temperature affects the requirements for relubrication. Thus, the extreme temperature resistance of an EMLA can be affected by special greases for low or high temperatures. (Ewellix, 2021c).

4.2.11 Anti-rotation

The purpose of an anti-rotation mechanism is to ensure and prevent a screw assembly from rotating and thus lengthening or shortening an EMLA's rod (Thomson, 2021b). The anti-rotation mechanism can be implemented in many ways, for example in Ewellix

SRSA EMLAs, the anti-rotation device is made by rail guides, in Ewellix CASM EMLAs, the thrust tube is equipped with an anti-rotation function and Tolomatic RSX EMLAs have an internal anti-rotation mechanism as the composite bearings prevent the thrust tube from rotation (Ewellix, 2021c; Tolomatic, 2021c).

4.2.12 Life cycle

The life cycle of an EMLA has a significant impact on the choice of the most competitive EMLA between different OEMs and can vary notably depending on the OEM and on the type of screw. Roller screws have more contact surfaces in their structure, which is why they usually have a significantly longer life cycle than ball screws. (Tolomatic, 2017).

Estimating the life cycle of an EMLA is important in new application development, in proactive maintenance planning and in preventing downtime of the application. In order to achieve a realistic, reliable and proper life cycle estimate, a considerable amount of data from innumerable test cycles is required. In long-term testing, the EMLAs are driven to the breaking point and the performance data and the number of cycles are used to create a life cycle curve. The load capacity percent is also changed between the test cycles of different EMLAs of the same model. (Linak, 2021a)

Similar to above-mentioned, test results can be used to measure the life cycle estimates of an EMLA OEM’s customers’ applications. OEMs such as Tolomatic and Linak have sizing tools available on their websites, into which the customer enters the application information, which includes for example, the motion profile, affecting loads, and stroke lengths of their own application to calculate the life cycle estimate of the EMLA. (Linak, 2021a).

In addition to the above-mentioned application information, a life cycle is affected by other factors that are more difficult to define, such as humidity, temperature fluctuations or momentary vibrations affecting the EMLA (Linak, 2021a). Lubrication starvation, negligent EMLA design, linear velocity, wear, contamination, and incorrect mounting can also affect negatively to life cycle or lead to premature failure. These factors should be carefully considered to ensure a long and maintenance-free life cycle. (Tolomatic, 2017).

4.2.13 Life cycle calculation

Typical hydraulic or pneumatic linear actuators have fewer components than EMLAs, but they still have more critical parts, such as compressor, hoses, valves, and filters. Difficulties with these components affect the entire system and can lead to machine failure.

In addition, fluid power systems are very susceptible to contamination, so the systems have poor reliability and rely on frequent maintenance. Thus, fluctuations in the life cycle are common in hydraulic and pneumatic systems. (Ewellix, 2021c).

The screw or the bearing are the most common failure points in EMLAs (Ewellix, 2021c). For these components, L_{10} life cycle can be calculated to provide the most accurate estimate of the overall lifetime. The calculation of the L_{10} is represented in the equation (3) and is defined as a value of the life cycle which is achieved by 90 percent of the identical screws or bearings, or alternatively, 10 percent of the identical screws or bearings can be expected to have failed as a result of fatigue. (Tolomatic, 2017).

The term dynamic load capacity, *C*, which is used in the L_{10} lifetime calculation (3), represents the constant load at which a screw or bearing nominally reaches one million revolutions. The magnitude of the dynamic load capacity depends on the diameter of the screw, the lead of the screw and the numerous rotating elements, balls, or rollers, inside the nut that simultaneously support the load. (Tolomatic, 2017).

Along the working cycle, the load is usually varying. In that case, it is necessary to calculate the equivalent load, F_e, acting on the screw. The calculation of the equivalent load with varying loads is represented in the equation (2). The life cycle of the screw has the same effect with the varying combined actual loads as with the constantly applied equivalent load. A constantly applied load is a load that does not change during the cycle. If the load of an application is constant during the movements, then the equivalent load is the same as the actual load. (Tolomatic, 2017).

The calculation of the equivalent load, F_e, can be written as follows:

$$F_e = \sqrt[3]{\frac{s_1(F_1)^3 + s_2(F_2)^3 + s_3(F_3) + s_n(F_n)^3}{s}} \tag{2}$$

Where:

F_n Each addition at separate load (*N*)

s Total travelled distance (*mm*) per working cycle (extend and retract stroke)

s_n Each addition of stroke (*mm*) at separate load

The rating of the lifetime L_{10} can be presented by the following equation, where the above-mentioned equivalent load, F_e is also utilized:

$$L_{10} = \left(\frac{C}{F_e}\right)^3 \cdot P \tag{3}$$

Where:

C Dynamic load capacity (*N*)

P Screw lead (*mm*)

The life cycle of an EMLA is often necessary to calculate over time, such as in years. The following formula (4) represents the life estimate in time:

$$L_y = \left(\frac{L_{10}}{\frac{S}{CpM \cdot 60\ min/hr \cdot HpD \cdot DpY}}\right) \cdot P \tag{4}$$

Where:

L_y Life estimate in years

CpM Cycles per minute

HpD Hours operated per day

DpY Days of operation per year. (Tolomatic, 2017).

4.3 Electromechanical linear actuator requirements

For each performance characteristic, the estimated limits are set that will allow an EMLA to succeed as a producer of linear motion in the estimated average MWM. Those limits are called as requirements. For each performance characteristic, an importance level is assigned based on its value creation and impact on the performance in the operation of the EMLA assembly at the estimated average MWM. The importance levels are determined for the comparative QFD analysis in chapter 5.

Table 5 is the basis for the requirements table that is used to clarify how each OEM selected for the QFD analysis meets the requirements. Maximum dynamic force is the most important performance characteristic of the QFD analysis. Based on the empirical research in this thesis, the maximum dynamic force significantly determines the competitiveness compared to other EMLA products from the same OEM. Accordingly, the importance level of 12 defines clearly the maximum dynamic force as the primary performance characteristic. The maximum dynamic force is often a visible part of the specifications and only less than half of the OEMs report maximum static force separately.

Thus, the maximum static force is excluded from the QFD analysis and its significance is reflected as part of the importance of the maximum dynamic force. Anti-rotation is also excluded from the QFD analysis as it is selectable for each product in the comparison. Therefore, no importance level is assigned for the anti-rotation. Life cycle and weight are estimated to be slightly more important performance characteristics than the remaining ones. Performance characteristics length, height and width all measure the size of the EMLA, so they get a combined importance level of 4. The higher the values for weight, length, height, and width, the more disadvantageous they are to the EMLA’s operation. For this reason, they are deducted from the total of the QFD's weighted rating, while other performance characteristics have a positive effect on an EMLA's operations and are added to the total.

Table 5. *A requirement table for each performance characteristic for an EMLA that produces linear motion in an average MWM.*

Performance characteristic	Requirement	Importance level
Maximum dynamic force	> 200 kN	12
Maximum static force	> 300 kN	-
Weight at 0 mm stroke	< 300 kg	3
Length without stroke	< 800 mm	2
Height	< 500 mm	1
Width	< 300 mm	1
Max stroke length	> 1000 mm	2
Ingress Protection	IP67	2
Max. linear velocity	> 600 mm/s	2
Operating temp. range	0-50 °C	2
Mechanical efficiency	> 80 %	2
Life cycle	> 500 km	4
Anti-rotation	Yes	-

The performance characteristics are selected using public EMLA OEM catalogs (Creative Motion Control, 2021b; Ewellix, 2021c; Parker, 2021; Royal Cylinders, 2021b; Tolomatic, 2021c) and their required limits and importance levels are, in addition to the EMLA catalogs, assessed based on proper performance in the average MWM which has been estimated using public MWM catalogs (Avant Tecno Oy, 2021; Kalmar, 2021; Ponsse, 2021; Sandvik, 2021a). Thus, the requirement limits are only indicative. Confidential information has also been partly obtained for this purpose, so the definition of the limits of the requirements will not be opened further in this thesis. However, the specifications underlying the requirements play major role in the OEM's catalogs and meeting the requirements is essential to the sufficient operation of EMLAs.

5. ANALYSIS AND RESULTS

The performance characteristics set in the study are based on the VOC of estimated average MWM. The first step of the QFD analysis is the identification of the critical performance characteristics based on the VOC. In the second step in chapter 4.3, the requirements are defined for the performance characteristics and the level of importance is determined for those numerically, based on the customer's perspective. Values from public EMLA OEM catalog specifications have then been collected for each performance characteristic. Next, the weighted ratings are formulated from the sum of weights and ratings. The weighted ratings are summed together to provide the relative results of product competitiveness.

5.1 Electromechanical linear actuators on the market

The characteristics of the best EMLAs on the market are tabulated next in the specification tables 6 and 7. The most competitive and best performing EMLA products in terms of the suitability for outdoor MWM use are distinguished for the more detailed requirement and QFD analysis. The size of the EMLA and the screw type and lead are selected for the products to achieve the maximum possible dynamic operational force and the longest life cycle. The high and low values of the important features, especially those that are essential for appropriate performance to meet the requirements, are highlighted in green and red. In addition, the missing but estimated values are highlighted in grey. The estimates for the grey values are detailed in chapter 5.2. The following limits are set to show the line for green and red values in specification tables:

- F_{maxdyn}, Maximum dynamic force: Over 200 kN, green. Under 100 kN, red.
- $F_{maxstat}$, Maximum static force: Over 300 kN, green. Under 150 kN, red.
- v_{max}, Maximum speed: Over 600 mm/s, green. Under 100 mm/s, red.
- IP, Ingress Protection class: IP67 or higher, green.

The most competitive EMLAs under consideration can perform above 200 kN maximum dynamic forces. Based on that, an equivalent dynamic force of 200 kN is used for life calculations to maintain comparability between the EMLAs. The missing values in the tables are not shown in the public specifications provided by the OEMs or, for example, for EMLAs with the maximum dynamic force of less than 200 kN, the life cycle cannot be calculated with the same equivalent dynamic force because the structure cannot withstand the dynamic force.

The mapping of the high load EMLAs on the market started at a rather early stage before a more detailed picture of the requirements, so the force capacities of every EMLA do not meet the requirements. However, the specification tables 6 and 7 present a broad picture of the state of the EMLA market. Based on the empirical research during the thesis, there is much more supply for the low force solutions which are not included in the study than for the high force ones. The specification table 6 shows that roller screw products dominate the market for high power actuators. Motiomax's product, which produces the highest maximum dynamic force, is an exception with its ball screw.

Tables 6 and 7 represent the EMLA market situation through specifications of well-known EMLA OEMs. Table 6 is the part 1, which provides information on the following EMLA specifications: OEM, product, screw type, maximum dynamic force (F_{maxdyn}), maximum static force ($F_{maxstat}$), screw diameter x screw lead (d_s x P), frame size, maximum stroke (s_{max}), maximum linear velocity (v_{max}), and ingress protection (IP). The products are arranged alphabetically by the OEM.

Table 6. *Specifications of EMLAs on the market, part 1 (Bosch Rexroth 2021; Creative Motion Control, 2021b; Ewellix, 2021c; Curtiss-Wright, 2021b; Curtiss-Wright, 2021a; Festo, 2021; HYDAC, 2021; Kollmorgen, 2021; Motiomax, 2021; Norgren, 2021; Parker, 2021; Power Jacks 2020; Royal Cylinders 2021b; Thomson 2021a; Tolomatic 2021c).*

OEM	Product	Screw type	F_{maxdyn} [kN]	$F_{maxstat}$ [kN]	d_s x P [mm]	Frame [mm]	s_{max} [mm]	v_{max} [mm/s]	IP
Creative Motion Control	CPD-350	Roller	70,3	-	x10	88,9	914,4	1194	IP67
Creative Motion Control	CPD-450	Roller	151,2	-	x12	114,3	1524	1016	IP67
Creative Motion Control	CPD-600	Roller	284,7	-	x18	152,4	2743	965	IP67
Creative Motion Control	CPD-800	Roller	556	-	x20	203,2	3658	689	IP67
Creative Motion Control	CPD-1000	Roller	1112	-	x25	254	3658	635	IP67
Ewellix	SRSA-4820	Roller	260	260	48x20	125	1200	1111	IP54
Ewellix	SRSA-6020	Roller	370	370	60x20	150	1300	889	IP54
Ewellix	SRSA-7520	Roller	500	500	75x20	180	1500	711	IP54
Exlar	FTX215	Roller	177,9	-	x30	215	600	875	IP65S
Exlar	FTP215	Roller	355,8	-	x12	215	600	351	IP65S
Festo	ESBF80	Ball	12	-	32x15	93	1500	620	IP65
Festo	ESBF100	Ball	17	-	40x20	110	1500	670	IP65
HYDAC	KineSys HEZ	Ball	500	-	-	-	3000	1000	IP65+
Kollmorgen	EC5	Ball	25	-	32x10	-	1500	1330	IP65
Motiomax	-	Ball	2000	-	-	-	-	1000	IP67
Norgren	E/809000	Ball	30,4	-	40x10	100	1500	1600	IP40
Parker	ETH080	Ball	17,8	-	32x5	95	1600	267	-
Parker	ETH100	Ball	50,8	-	50x20	120	2000	622	-
Parker	ETH125	Ball	81,4	-	63x20	150	2000	684	-
Parker	XFC140	Roller	80	160	48x10	139,7	2000	444	-
Parker	XFC165	Roller	120	240	60x20	165,1	2000	712	-
Parker	XFC190	Roller	178	356	75x20	190,5	2000	568	-
Power Jacks	Rolaram R175	Roller	225	335	-	206	2200	4	IP55
Power Jacks	Rolaram R225	Roller	300	450	-	270	3000	6	IP55
Power Jacks	Rolaram R250	Roller	386	600	-	285	3000	12	IP55
Rexroth	EMC-080	Ball	22	-	32x10	95	1500	500	IP65
Rexroth	EMC-100	Ball	29	-	40x20	115	1500	730	IP65
Rexroth	EMC-100XC	Ball	56	-	50x10	115	1500	500	IP65
Royal Cylinders	E32	Roller	169	306,9	36x30	165,1	609,6	2400	-
Royal Cylinders	E50	Roller	311,4	602,9	56x30	165,1	914,4	1300	-
Thomson	Electrak HD	Ball	16	-	-	-	1000	70	IP69
Tolomatic	RSX080	Roller	80	-	36x10	152,4	890	701	IP67
Tolomatic	RSX096	Roller	133,5	-	42x12	196,9	800	759	IP67
Tolomatic	RSX128	Roller	222,4	-	64x10	279,4	665	500	IP67

Table 7 is the part 2, which provides information on the following EMLA specifications: OEM, product, weight at 0 mm stroke, m_0, increase in weight per 100 mm stroke, m_{100}, maximum height of parallel configuration, h_{max}, length, l, maximum width, w_{max}, maximum allowable input torque, M_{max}, life cycle, L_{10}, ambient temperature, T, and mechanical efficiency, η. The life cycle, L_{10}, in kilometers is the value which 90% of identical EMLAs can be expected to reach and it is calculated with 200 kN equivalent dynamic force.

Table 7. *Specifications of EMLAs on the market, part 2 (Bosch Rexroth 2021; Creative Motion Control, 2021b; Ewellix, 2021c; Curtiss-Wright, 2021b; Curtiss-Wright, 2021a; Festo, 2021; HYDAC, 2021; Kollmorgen, 2021; Motiomax, 2021; Norgren, 2021; Parker, 2021; Power Jacks 2020; Royal Cylinders 2021b; Thomson 2021a; Tolomatic 2021c).*

OEM	Product	m_0 [kg]	m_{100} [kg]	h_{max} [mm]	l [mm]	w_{max} [mm]	M_{max} [Nm]	L_{10} [km]	T [°C]	η [%]
Creative Motion Control	CPD-350	21,3	2,1	231,1	401,3	142,2	123	-	-26,1…+73,9	88,5
Creative Motion Control	CPD-450	46,6	3,5	292,1	579,1	177,8	319	-	-26,1…+73,9	88,2
Creative Motion Control	CPD-600	107,8	7	381	721,3	228,6	903	181,4	-26,1…+73,9	87,9
Creative Motion Control	CPD-800	286,1	13,7	533,4	901,6	330,2	2000	1075	-26,1…+73,9	88,3
Creative Motion Control	CPD-1000	512	30	723,9	1127	450,7	5200	12896	-26,1…+73,9	84,9
Ewellix	SRSA-4820	174,6	5,7	470	560	210	1031	-	0…+40	80
Ewellix	SRSA-6020	206	8,9	490	656,5	210	1467	154,1	0…+40	80
Ewellix	SRSA-7520	309,5	11,3	640	773	280	2004	467,9	0…+40	79
Exlar	FTX215	103	10,2	533,4	695,9	292	976	-	0…+85	85
Exlar	FTP215	127	10,2	533,4	695,9	292	850	-	0…+85	85
Festo	ESBF80	7,4	1,55	-	-	-	33,7	-	0…+60	-
Festo	ESBF100	11,1	1,93	-	-	-	63,7	-	0…+60	-
HYDAC	KineSys HEZ	-	-	-	-	-	-	-	-	-
Kollmorgen	EC5	-	-	-	-	-	-	-	-	-
Motiomax	-	-	-	-	-	-	-	-	-	80-90
Norgren	E/809000	6	1,5	-	-	-	92,2	-	0…+60	-
Parker	ETH080	6,9	1,87	233,5	-	95	17,5	-	-10…+40	81
Parker	ETH100	-	-	347	-	120	200	-	-10…+40	81
Parker	ETH125	-	-	450	-	150	320	-	-10…+40	81
Parker	XFC140	62,1	4,53	332,2	465	139,7	-	-	-23…+73	88,3
Parker	XFC165	110,7	7,17	379,1	565	165,1	-	-	-23…+73	90,4
Parker	XFC190	171,9	9,48	455,5	665	190,5	-	-	-23…+73	91
Power Jacks	Rolaram R175	158	3	438	-	255	-	-	-30…+70	80
Power Jacks	Rolaram R225	297	5,1	527	-	306	-	-	-30…+70	80
Power Jacks	Rolaram R250	483	5,8	581	-	350	-	-	-30…+70	80
Rexroth	EMC-080	9,7	1,5	324	320	160	38,9	-	-10…+50	90
Rexroth	EMC-100	10,5	2,5	324	343	160	103	-	-10…+50	90
Rexroth	EMC-100XC	16,8	3,1	375	467,5	197	99	-	-10…+50	90
Royal Cylinders	E32	-	-	431,8	717,6	304,8	-	-	-	-
Royal Cylinders	E50	247,1	-	431,8	717,6	304,8	-	821,6	-	-
Thomson	Electrak HD	9,4	-	-	-	-	-	-	-	-
Tolomatic	RSX080	42,1	3,1	355,6	510,7	177,8	-	-	-40…+60	77-80
Tolomatic	RSX096	74,2	4,1	409,6	655,9	209,6	-	-	-40…+60	77-80
Tolomatic	RSX128	208,5	7,9	584,2	883,6	285,8	-	108,5	-40…+60	77-80

Table 8 contains the specifications of EMLA products with a maximum dynamic force greater than 200 kN. The values are the same as in Table 6, but the products are arranged according to the maximum dynamic force. Motiomax impresses by offering EMLA solutions up to 2000 kN, but does not have a public catalog, as they manufacture their products according to customer requirements (Motiomax, 2021). Therefore, Motiomax is not suitable for QFD analysis due to insufficient data on performance characteristics. It is still very likely that Motiomax would achieve the highest result in the QFD analysis due to its high maximum dynamic force.

HYDAC (2021) catalog provide information that 500 kN maximum dynamic force is achievable by customized planetary roller screw solution, but for the rest of the information, too much is left open for the OEM to make sense to include it in the QFD analysis. Power Jacks (2020) has many options for high maximum dynamic force, but according to their catalog, linear speeds will remain very low in non-special products, and their application solutions focus more on industry rather than MWMs. Thus, Power Jacks is excluded from the QFD analysis. Exlar's high-performance FTP215 product is also omitted from the QFD analysis as it is intended for use in press applications only (Curtiss-Wright, 2021a).

Table 8. *Specifications of EMLAs with a maximum dynamic force greater than 200 kN, part 1.*

OEM	Product	Screw type	F_{maxdyn} [kN]	$F_{maxstat}$ [kN]	d_s x P [mm]	Frame [mm]	s_{max} [mm]	v_{max} [mm/s]	IP
Motiomax	-	Ball	2000	-	-	-	-	1000	IP67
Creative Motion Control	CPD-1000	Roller	1112	-	x25	254	3658	635	IP67
Creative Motion Control	CPD-800	Roller	556	-	x20	203,2	3658	689	IP67
Ewellix	SRSA-7520	Roller	500	500	75x20	180	1500	711	IP54
HYDAC	KineSys HEZ	Ball	500	-	-	-	3000	1000	IP65+
Power Jacks	Rolaram R250	Roller	386	600	-	285	3000	11	IP55
Ewellix	SRSA-6020	Roller	370	370	60x20	150	1300	889	IP54
Exlar	FTP215	Roller	355,8	-	x12	215	600	351	IP65S
Royal Cylinders	E50	Roller	311,4	602,9	56x30	165,1	914,4	1300	-
Power Jacks	Rolaram R225	Roller	300	450	-	270	3000	6	IP55
Creative Motion Control	CPD-600	Roller	284,7	-	x18	152,4	2743	965	IP67
Ewellix	SRSA-4820	Roller	260	260	48x20	125	1200	1111	IP54
Power Jacks	Rolaram R175	Roller	225	335	-	206	2200	4	IP55
Tolomatic	RSX128	Roller	222,4	-	64x10	279,4	665	500	IP67

Table 9 contains the same specifications as table 7 for products that achieve a maximum dynamic force above 200 kN. The products are in order from top to bottom based on the highest maximum dynamic force as shown in table 8. Table 9 represents how the weight of the product typically increases in relative to the maximum dynamic force. However, there are exceptions and Power Jacks products, for example, weigh heavily in terms of their ability to produce maximum dynamic force.

Table 9. *Specifications of EMLAs with a maximum dynamic force greater than 200 kN, part 2.*

OEM	Product	m_0 [kg]	m_{100} [kg]	h_{max} [mm]	l [mm]	w_{max} [mm]	M_{max} [Nm]	L_{10} [km]	T [°C]	η [%]
Motiomax	-	-	-	-	-	-	-	-	-	80-90
Creative Motion Control	CPD-1000	512	30	723,9	1127	450,7	5200	12896	-26,1…+73,9	84,9
Creative Motion Control	CPD-800	286,1	13,7	533,4	901,6	330,2	2000	1075	-26,1…+73,9	88,3
Ewellix	SRSA-7520	309,5	11,3	640	773	280	2004	467,9	0…+40	79
HYDAC	KineSys HEZ	-	-	-	-	-	-	-	-	-
Power Jacks	Rolaram R250	483	5,8	581	-	350	-	-	-30…+70	80
Ewellix	SRSA-6020	206	8,9	490	656,5	210	1467	154,1	0…+40	80
Exlar	FTP215	127	10,2	533,4	695,9	292	850	-	0…+85	85
Royal Cylinders	E50	247,1	-	431,8	717,6	304,8	-	821,6	-	-
Power Jacks	Rolaram R225	297	5,1	527	-	306	-	-	-30…+70	80
Creative Motion Control	CPD-600	107,8	7	381	721,3	228,6	903	181,4	-26,1…+73,9	87,9
Ewellix	SRSA-4820	174,6	5,7	470	560	210	1031	-	0…+40	80
Power Jacks	Rolaram R175	158	3	438	-	255	-	-	-30…+70	80
Tolomatic	RSX128	208,5	7,9	584,2	883,6	285,8	-	108,5	-40…+60	77-80

The specification tables show, at least on a OEM-by-OEM basis, that the size of the EMLA product increases as the force capacity increases and the maximum linear velocity decreases accordingly as the size increases. The maximum static force is typically slightly higher than the maximum dynamic force and only few OEMs provide static force capacity separately.

5.2 Calculations and considerations for the most competitive electromechanical linear actuators

This chapter represents the life cycle calculations and other important considerations for the most competitive EMLAs that are suitable for MWM applications. The formulas for the life cycle calculation are represented in the chapter 4.2.13. The calculation does not need to be performed for some individual OEMs, as they provide lifetime data in the form of a graph.

5.2.1 Creative Motion Control CPD series

There are three EMLAs in the CPD series, the CPD-600, CPD-800, and CPD-1000, which are appropriate in comparison as they reach above 200 kN maximum dynamic forces. The maximum dynamic forces are 284,7 kN for CPD-600, 556 kN for CPD-800 and 1112,1 kN for CPD-1000 EMLA, so the force capacity range is one of the best in the market in terms of the maximum dynamic forces.

Creative Motion Control roller screw catalog (Creative Motion Control, 2021d) provides values for the dynamic load capacity, *C*, but instead of CPD series EMLAs, these dynamic load ratings are only assigned to the roller screws of different sizes. However, the catalog of CPD series EMLAs (Creative Motion Control, 2021b) shows the screw leads for those products, which give an indication of the roller screws intended for them.

The dynamic load capacity of the largest 150x50 (d_s *x P*) roller screw available reaches 2208,1 kN. However, the screw lead of the largest CPD-1000 EMLA is only 25 mm, and no corresponding screw is directly available for this. As a result, it is assumed that the roller screw suitable for calculating the life cycle is 120x20 with a screw lead of 5 mm less. The dynamic load capacity of the 120x20 roller screw is 1604 kN.

According to the catalog, the screw lead of the CPD-800 actuator is 20 mm and for the CPD-600 the screw lead is 18 mm. The most suitable roller screw for the CPD-800 actuator might be 75x20 with 754,7 kN dynamic load capacity and for CPD-600 it might be 64x18 with 432 kN dynamic load capacity. These are only appropriate estimates for the life calculations and thus not 100 percent reliable.

Equation (5) represents that with the dynamic load capacity of 1604 kN, the screw lead of 25 mm and the equivalent force of 200 kN, the L_{10} life cycle of the CPD-1000 EMLA is 12 896 km. The calculation is based on the equation (3) shown in the chapter 4.2.13. Calculated in the same way, the life cycle of the CPD-800 EMLA is 1075 km, and the life cycle, L_{10}, of the CPD-600 product is 181,4 km with the 200 kN equivalent load.

$$L_{10} = \left(\frac{C}{F_e}\right)^3 \cdot P = \left(\frac{1604\ kN}{200\ \mathrm{kN}}\right)^3 \cdot 25\ \mathrm{mm} = 12\ 896{,}2\ km \tag{5}$$

Where:

C Dynamic load capacity (*N*)

F_e Equivalent load (*N*)

P Screw lead (*mm*)

As with the other CPD series EMLAs, no values for length, height, or width are given for the CPD-1000 product in the catalog. These numeric values for CPD-1000 are estimated based on the values of the CPD-450, CPD-600, and CPD-800 products. The length between the above-mentioned products from smaller to larger has increased by an average of about 25 percent, so the length of the CPD-1000 product is estimated to be 25 percent higher than with the CPD-800 EMLA. Height and width are also estimated using a similar formula that relies on the average increase in value. These estimates are used in the QFD analysis.

The weights of the CPD series EMLAs are given with either oil filled or grease lubrication and depending on the stroke length from a stroke length of approximately 100 mm. Therefore, the weight with a stroke length of 0 mm must be estimated. The weight of the CPD-1000 EMLA increases by an average of 30 kg at 100 mm stroke lengths, so this is subtracted from the weight of 100 mm stroke length of 542 kg, resulting in a weight of 512 kg for a 0 mm stroke length. The same applies to the other CPD EMLAs.

Table 10 shows how Creative Motion Control's three most competitive EMLAs meet the requirements of operation in estimated average MWM. Most of the requirements are met properly, but CPD-800 and CPD-1000 products especially may have problems in terms of the size to fit in the same space as a replacement for an old HLA. On the other hand, the life cycle of the smallest CPD-600 product remains short if the equivalent load is 200 kN. The maximum static forces of CPD-series EMLAs are not published in the Creative Motion Control's (2021b) catalog, so they are defined to be equal to or greater than the maximum dynamic force.

Table 10. *Requirements for each Creative Motion Control EMLA (Creative Motion Control, 2021b).*

Performance characteristic	Requirement	Importance	Results CPD-600	Results CPD-800	Results CPD-1000
Maximum dynamic force	> 200 kN	12	284,7 kN	556 kN	1112,1 kN
Maximum static force	> 300 kN	-	284,7 kN+	556 kN+	1112,1 kN+
Weight at 0 mm stroke	< 300 kg	3	107,8 kg	286,1 kg	512 kg
Length without stroke	< 800 mm	2	721,3 mm	901,6 mm	1127 mm
Height	< 500 mm	1	381 mm	533,4 mm	723,9 mm
Width	< 300 mm	1	228,6 mm	330,2 mm	450,7 mm
Max stroke length	> 1000 mm	2	3658 mm	3658 mm	2743 mm
Ingress Protection	IP67 or higher	2	IP67	IP67	IP67
Max. linear velocity	> 600 mm/s	2	965 mm/s	689 mm/s	635 mm/s
Operating temp. range	0-50 °C	2	-26,1…+73,9 °C	-26,1…+73,9 °C	-26,1…+73,9 °C
Mechanical efficiency	> 80 %	2	87,9 %	88,3 %	84,9 %
Life cycle (200 kN)	> 500 km	4	181,4 km	1075 km	12896 km
Anti-rotation	Yes	-	Yes	Yes	Yes

Pass	Fail

5.2.2 Ewellix SRSA series

The SRSA-U-48xx EMLA could have been included in the requirement and QFD analysis based on a maximum dynamic force of 260 kN, but according to the Ewellix (2021c) catalog, the maximum allowable force usable to apply to the theoretical life cycle calculation is 140 kN. As a result, the SRSA48xx product is excluded from the requirements and QFD analysis.

According to the Ewellix (2021c) high performance EMLA catalog, the maximum dynamic force of the SRSA-U-60xx linear unit is 370 kN and the maximum force used for life cycle calculations is 250 kN. Similarly, Ewellix's strongest EMLA, the SRSA-U-75xx, has a maximum dynamic force of 500 kN and a maximum force for life cycle calculations of 450 kN. The longest life cycle and the highest maximum dynamic load capacity are achieved in both products with a screw lead of 20 mm. Therefore, the products under consideration are SRSA-U-6020 and SRSA-U-7520.

Figure 26 represents the life cycle performance graph for an Ewellix SRSA-U-60xx EMLA. The graph shows the equivalent dynamic axial load as a function of lifetime in kilometers. In order to obtain the accurate value for the L_{10} life cycle, calculation is performed in equation (6).

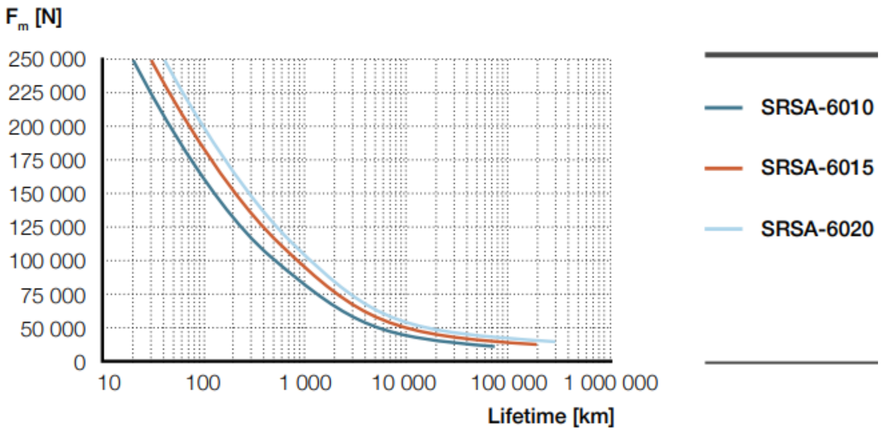


Figure 26. *The lifetime performance graph for the Ewellix SRSA-U-60xx EMLA (Ewellix, 2021c).*

In the equation (6), the 395 kN dynamic load capacity and the 20 mm screw lead from the Ewellix (2021c) catalog have been used in the calculation. Based on the calculation, the life cycle of 154,1 km is achieved for the SRSA-6020 EMLA.

$$L_{10} = \left(\frac{C}{F_e}\right)^3 \cdot P = \left(\frac{395\ kN}{200\ \mathrm{kN}}\right)^3 \cdot 20\ \mathrm{mm} = 154{,}1\ km \tag{6}$$

Where:

C Dynamic load capacity (*N*)

F_e Equivalent load (*N*)

P Screw lead (*mm*)

Figure 27 shows a lifetime performance graph for an Ewellix SRSA-U-75xx EMLA, where the equivalent dynamic axial load is represented as a function of lifetime in kilometers. Viewed with an equivalent load of 200 kN, the lifetime between 400-500 km is reached. The exact value is 467,9 km, which is calculated similarly to the equation (6), using the 572 kN dynamic load capacity and the 20 mm screw lead from the Ewellix catalog. (Ewellix, 2021c).

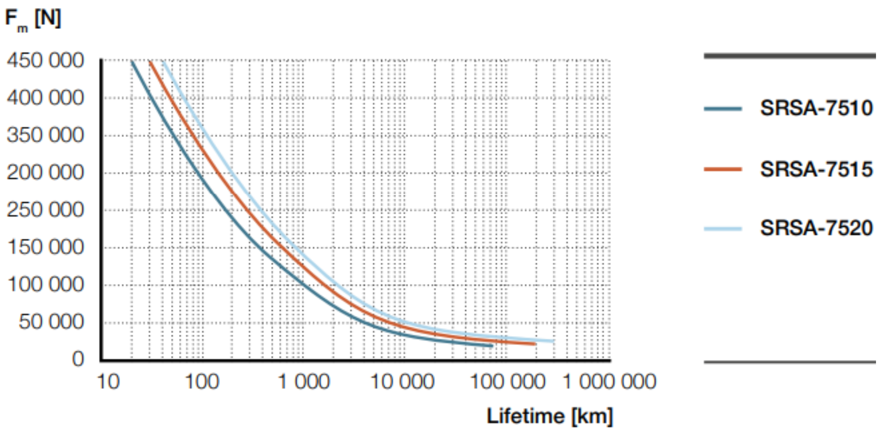


Figure 27. *The lifetime performance graph for the Ewellix SRSA-U-75xx EMLA (Ewellix, 2021c).*

Table 11 represents how the Ewellix's two most competitive EMLAs meet the requirements of operation in estimated average MWM. The size and weight are slightly below the targets with the larger SRSA-7520 EMLA and both products have problems with ingress protection, operating temperature, mechanical efficiency, and life cycle. With the exception of the SRSA-6020's life cycle, the requirements still do not fall far short of the desired limits.

Table 11. *Requirements for each Ewellix SRSA EMLA (Ewellix, 2021c).*

Performance characteristic	Requirement	Importance	Results SRSA-6020	Results SRSA-7520
Maximum dynamic force	> 200 kN	12	370 kN	500 kN
Maximum static force	> 300 kN	-	370 kN	500 kN
Weight at 0 mm stroke	< 300 kg	3	206 kg	309,5 kg
Length without stroke	< 800 mm	2	656,5 mm	773 mm
Height	< 500 mm	1	490 mm	640 mm
Width	< 300 mm	1	210 mm	280 mm
Max stroke length	> 1000 mm	2	1300 mm	1500 mm
Ingress Protection	IP67 or higher	2	IP54	IP54
Max. linear velocity	> 600 mm/s	2	889 mm/s	711 mm/s
Operating temp. range	0-50 °C	2	0…+40 °C	0…+40 °C
Mechanical efficiency	> 80 %	2	80 %	79 %
Life cycle (200 kN)	> 500 km	4	154,1 km	467,9 km
Anti-rotation	Yes	-	Yes	Yes

Pass	Fail

5.2.3 Royal Cylinders E50

The Royal Cylinders brand E50 EMLA is suitable for inspection with the maximum dynamic force of 311,4 kN, or 70 000 lbs, as it is indicated in the Royal Cylinders (2021b) catalog. Another of the OEM's EMLAs, the smaller E32, has the maximum dynamic force of up to 169 kN and is therefore excluded from the review.

It can be seen from Figure 28 that the life cycle of the E50 product is between about 32 and 33 million inches, or about 812-838 kilometers. Dynamic load capacity of 135528 lbs or 602,9 kN is also available, so the exact lifetime is calculated in the equation (7).

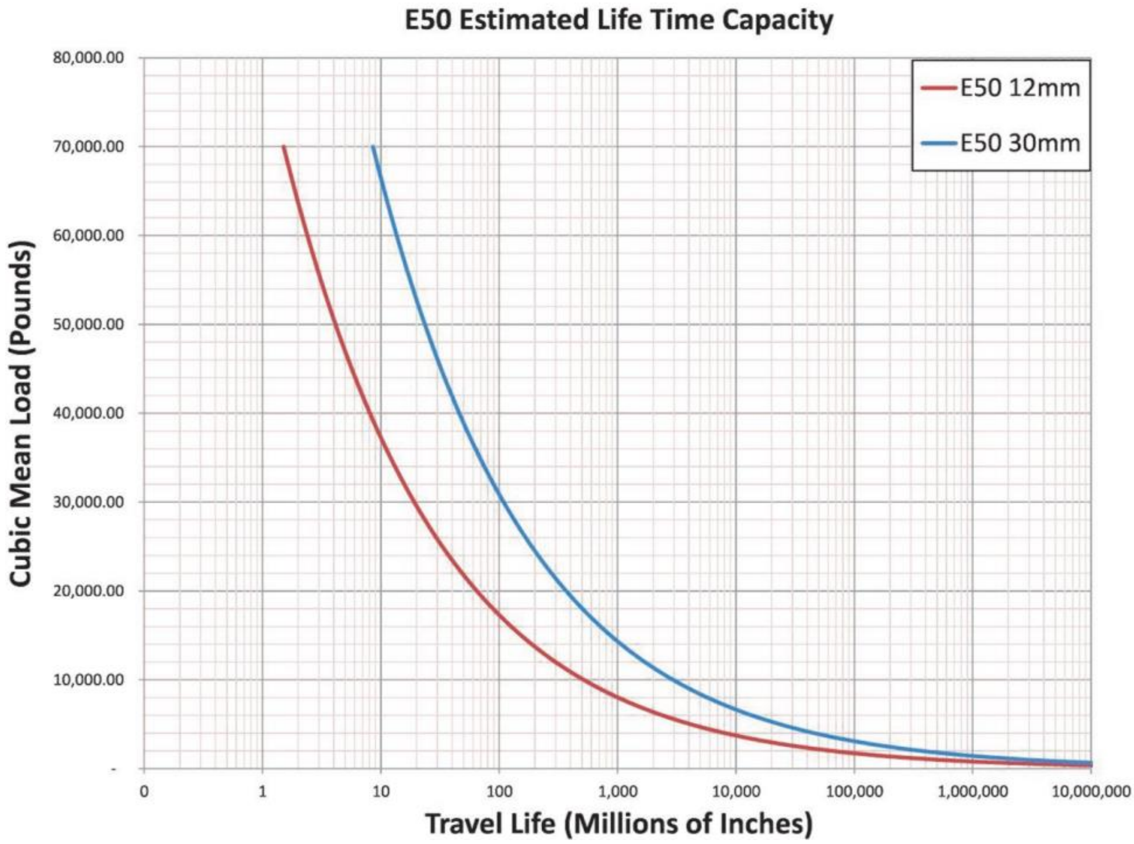


Figure 28. *The estimated lifetime capacity for the Royal Cylinders E50 EMLA (Royal Cylinders, 2021b).*

Equation (7) represents the life cycle calculation for the Royal Cylinders E50 product. The dynamic load capacity of 602,9 kN, the equivalent force of 200 kN and a screw lead of 30 mm is used in the calculation, which results in a longer life cycle than a lead of 12 mm. Thus, the exact life cycle expectancy of the E50 EMLA is 821,6 km.

$$L_{10} = \left(\frac{C}{F_e}\right)^3 \cdot P = \left(\frac{602{,}9\ kN}{200\ \mathrm{kN}}\right)^3 \cdot 30\ \mathrm{mm} = 821{,}6\ km \tag{7}$$

Where:

C	Dynamic load capacity (*N*)
F_e	Equivalent load (*N*)
P	Screw lead (*mm*)

Royal Cylinders (2021b) does not provide the EMLA weight information in its catalog. Therefore, the weight of the E50 EMLA must be estimated for the QFD analysis. The ratio of the length of the largest EMLAs of Creative Motion Control, Ewellix and Tolomatic to their weight is used to calculate the weight estimate. The average weight to length ratio of the above EMLAs is about 0,34. When multiplying the ratio by the 717,6 mm length of the Royal Cylinders E50 EMLA, the result of the weight estimate is 247,1 kg. This estimate is used in the QFD analysis. The mechanical efficiency of the screw is also not available in the catalog, so it is estimated to be 80 percent. The hidden value is thus estimated to be at the bottom of the comparable OEMs.

Table 12 shows the performance of the Royal Cylinders E50 EMLA at the estimated average MWM based on the requirements. The force requirements are met properly, especially regarding to the almost half higher maximum static force. The fulfillment of the weight requirement cannot be considered certain, as it has been estimated. The widest point of the structure exceeds 300 mm, and the stroke length 914,4 mm does not quite reach 1000 mm. The Royal Cylinders (2021b) catalog does not provide information on IP classification. In addition to the weight and the mechanical efficiency, the Royal Cylinders (2021b) catalog does not provide information on IP rating or ambient temperature limits. The life cycle is relatively high, and the possibility of an optional anti-rotation is provided.

Table 12. *Requirements for Royal Cylinders E50 EMLA (Royal Cylinders, 2021b).*

Performance characteristic	Requirement	Importance	Results E50
Maximum dynamic force	> 200 kN	12	311,4 kN
Maximum static force	> 300 kN	-	602,9 kN
Weight at 0 mm stroke	< 300 kg	3	247,1 kg
Length without stroke	< 800 mm	2	717,6 mm
Height	< 500 mm	1	431,8 mm
Width	< 300 mm	1	304,8 mm
Max stroke length	> 1000 mm	2	914,4 mm
Ingress Protection	IP67 or higher	2	-
Max. linear velocity	> 600 mm/s	2	1300 mm/s
Operating temp. range	0-50 °C	2	-
Mechanical efficiency	> 80 %	2	-
Life cycle (200 kN)	> 500 km	4	821,6 km
Anti-rotation	Yes	-	Yes

Pass	Fail

5.2.4 Tolomatic RSX128

The largest of Tolomatic's EMLAs, RSX128, is sufficient for consideration with the dynamic maximum force of 222,4 kN. Based on the equation (8) and the information in the Tolomatic (2021c) RSX EMLA catalog, the life cycle of the Tolomatic's most powerful RSX128 product is 108,5 kilometers. The calculation uses 442,7 kN dynamic load capacity, 10 mm screw lead and 200 kN force as the equivalent load. The result shows a large effect of screw lead on life cycle, as the lifetime of Ewellix's SRSA 6020 EMLA is almost 50 km longer with a 20 mm screw lead, although the dynamic load capacity is about 50 kN lower.

$$L_{10} = \left(\frac{C}{F_e}\right)^3 \cdot P = \left(\frac{442{,}7\ kN}{200\ \mathrm{kN}}\right)^3 \cdot 10\ \mathrm{mm} = 108{,}5\ km \tag{8}$$

Where:

C Dynamic load capacity (*N*)

F_e Equivalent load (*N*)

P Screw lead (*mm*)

Table 13 represents how the Tolomaric's most competitive EMLA meets the requirements of operation in estimated average MWM. The maximum static forces of the RSX series EMLAs are not published in the Tolomatic's (2021c) catalog, so with the RSX128 product it is defined to be equal to or greater than the maximum dynamic force. In terms of the force capacity, the RSX128 EMLA is relatively large in size. The mechanical efficiency of the screw is not available in the Tolomatic catalog, so it is defined to be 80 percent in the QFD analysis as it is with the Royal Cylinders. The stroke length could be longer, but the buckling load limits the stroke length to 665 mm if full force capacity is desired. The Tolomatic RSX128 EMLA is able to operate very reliably even in harsh environments, as its products are IP67 rated and have an extensive temperature range.

Table 13. *Requirements for Tolomatic RSX128 EMLA (Tolomatic, 2021c).*

Performance characteristic	Requirement	Importance	Results E50
Maximum dynamic force	> 200 kN	12	222,4 kN
Maximum static force	> 300 kN	-	222,4+ kN
Weight at 0 mm stroke	< 300 kg	3	208,5 kg
Length without stroke	< 800 mm	2	883,6 mm
Height	< 500 mm	1	584,2 mm
Width	< 300 mm	1	285,8mm
Max stroke length	> 1000 mm	2	665 mm
Ingress Protection	IP67 or higher	2	IP67
Max. linear velocity	> 600 mm/s	2	665 mm/s
Operating temp. range	0-50 °C	2	-40…+60 °C
Mechanical efficiency	> 80 %	2	-
Life cycle (200 kN)	> 500 km	4	108,5 km
Anti-rotation	Yes	-	Yes

Pass	Fail

5.3 Quality Function Deployment analysis results

The first step of the QFD analysis is to establish the most critical performance characteristics for the EMLA based on the VOC of estimated average MWM. In the second step, the technical requirements are defined for the performance characteristics and the level of importance is determined for those numerically, based on the EMLA's proper performance in the estimated average MWM. The performance characteristics and the requirements are shown in the chapter 4.3.

Next, ratings are formed from the value of that performance characteristic and dividing it by the sum of the same value of it and the other products. In the other words, the rating is the relative share of the value of the same performance characteristic of the products. The weighted ratings for every performance characteristic are formulated from the multiplication of the importance levels and the ratings. The weighted ratings are summed together to provide the relative results of the competitiveness of each product.

The values of the weighted ratings increase the outcome of the sum that determines the level of performance of that EMLA product. The exceptions are weight, length, height, and width which decrease the outcome of the sum. These performance characteristics define the size characteristics of an EMLA, and the smaller the assembly of the EMLA is relative to the maximum dynamic force it produces, the more competitive the EMLA is.

Table 14 represents the QFD analysis and its results. The sum row shows the results and based on those; the Creative Motion Control's CPD-1000 is by far the most competitive EMLA in the comparison. The CPD-1000 is particularly impressing with the high maximum dynamic force and long life cycle. The second most competitive EMLA is also a product from the same OEM, the consistently high quality CPD-800, and the third and fourth placed EMLAs are Ewellix SRSA-U-7520 and SRSA-U-6020. The Ewellix's products are of high quality, but they lag significantly behind Creative Motion Control's products in terms of maximum dynamic forces and life cycle. The fifth and sixth products in the comparison are the Royal Cylinders E50 and Tolomatic RSX128, whose maximum dynamic forces especially in relation to their weights are too low compared to the other products.

Table 14. *The Quality Function Deployment analysis.*

		CMC CPD-1000			Ewellix SRSA-U-7520			Royal Cylinders E50		
Performance characteristic	Importance	Value	Rating	Weighted Rating	Value	Rating	Weighted Rating	Value	Rating	Weighted Rating
Max. dynamic force [kN]	12	1112	0,362	4,344	500	0,163	1,953	311,4	0,101	1,216
Weight at 0 mm stroke [kg]	3	512	0,289	0,868	309,5	0,175	0,525	247,1	0,140	0,419
Lenght [mm]	2	1127	0,223	0,445	773	0,153	0,306	717,6	0,142	0,284
Height [mm]	1	723,9	0,213	0,213	640	0,188	0,188	431,8	0,127	0,127
Width [mm]	1	450,7	0,242	0,242	280	0,150	0,150	304,8	0,164	0,164
Max. stroke length (mm)	2	3658	0,313	0,626	1500	0,128	0,257	914,4	0,078	0,156
Ingress Protection [IP]	2	67	0,217	0,434	54	0,175	0,350	0	0	0
Max. linear velocity [mm/s]	2	635	0,134	0,269	711	0,151	0,301	1300	0,275	0,550
Operating temp. range [°C]	2	73,9	0,219	0,438	40	0,118	0,237	50	0,148	0,296
Mechanical efficiency [%]	2	84,9	0,172	0,345	79	0,161	0,321	80	0,163	0,325
Life [km]	4	12896	0,831	3,323	467,9	0,030	0,121	821,6	0,053	0,212
Sum				8,009			2,370			1,763

		Tolomatic RSX128			CMC CPD-800			Ewellix SRSA-U-6020		
Performance characteristic	Importance	Value	Rating	Weighted Rating	Value	Rating	Weighted Rating	Value	Rating	Weighted Rating
Max. dynamic force [kN]	12	222,4	0,072	0,869	556	0,181	2,172	370	0,120	1,445
Weight at 0 mm stroke [kg]	3	208,5	0,118	0,353	286,1	0,162	0,485	206	0,116	0,349
Lenght [mm]	2	884	0,175	0,349	901,6	0,178	0,356	656,5	0,130	0,260
Height [mm]	1	584	0,172	0,172	533,4	0,157	0,157	490	0,144	0,144
Width [mm]	1	286	0,154	0,154	330,2	0,177	0,177	210	0,113	0,113
Max. stroke length (mm)	2	665	0,057	0,114	3658	0,313	0,626	1300	0,111	0,222
Ingress Protection [IP]	2	67	0,217	0,434	67	0,217	0,434	54	0,175	0,350
Max. linear velocity [mm/s]	2	500	0,106	0,212	689	0,146	0,292	889	0,188	0,376
Operating temp. range [°C]	2	60	0,178	0,355	73,9	0,219	0,438	40	0,118	0,237
Mechanical efficiency [%]	2	80	0,163	0,325	88,3	0,179	0,359	80	0,163	0,325
Life [km]	4	108,5	0,007	0,028	1075	0,069	0,277	154,1	0,010	0,040
Sum				1,308			3,421			2,130

The QFD analysis is based on the specifications (Table 6 and 7) collected from public catalogs of EMLA OEMs and does not include every competitive OEM, due to the limited public information available. Motiomax with its maximum dynamic forces up to 2000 kN would almost certainly have achieved the best results from an OEM, but the company offers customized products and therefore no catalogs of public specifications are available.

6. CONCLUSIONS

The purpose of this work has been to determine the extent to which EMLAs are capable to meet the requirements of HLAs in MWMs. The public catalogs of EMLA and MWM OEMs have been used to collect the specifications and to define the requirements and performance characteristics for EMLAs. Based on them, the comparative QFD analysis has been performed, in which the relative order of the most competitive EMLAs has been determined. The understanding of the EMLA market is also facilitated by the OEM-specific requirement tables and the specification tables which include more OEMs than the QFD analysis. Table 15 presents the resulted rankings of the QFD analysis based on product competitiveness.

Table 15. *The results from the QFD analysis.*

1. CMC CPD-1000	8,009
2. CMC CPD-800	3,421
3. Ewellix SRSA-U-7520	2,37
4. Ewellix SRSA-U-6020	2,13
5. Royal Cylinders E50	1,763
6. Tolomatic RSX128	1,308

Based on a QFD analysis with eleven different performance characteristics, the most competitive OEM in the EMLA market is Creative Motion Control. However, due to a lack of information, the products of Motiomax, which manufactures customer-specific products, are not included in the analysis. Table 16 presents the products on the market for maximum dynamic forces above 200 kN.

Table 16. *Specifications of the EMLAs with the maximum dynamic force greater than 200 kN.*

OEM	Product	F_{maxdyn} [kN]
Motiomax	-	2000
Creative Motion Control	CPD-1000	1112
Creative Motion Control	CPD-800	556
Ewellix	SRSA-7520	500
HYDAC	KineSys HEZ	500
Power Jacks	Rolaram R250	386
Ewellix	SRSA-6020	370
Exlar	FTP215	355,8
Royal Cylinders	E50	311,4
Power Jacks	Rolaram R225	300
Creative Motion Control	CPD-600	284,7
Ewellix	SRSA-4820	260
Power Jacks	Rolaram R175	225
Tolomatic	RSX128	222,4

As there are only few products on the market with the dynamic force capacity of more than 200 kN, the maximum dynamic forces of 2000 kN achieved by Motiomax especially are impressive. Hydac, Power Jacks, and Exlar are also excluded from the QFD analysis because Hydac achieves a force of 500 kN only with a custom-made special product, the low linear velocities of Power Jacks products are not suitable for MWM use, and Exlar's most powerful product is offered for press applications only (Curtiss-Wright, 2021a; HYDAC, 2021; Power Jacks, 2020).

The maximum dynamic force of an EMLA is the most significant performance characteristic and classified according to it, two OEMs, Creative Motion Control and Motiomax, are capable of manufacturing EMLAs that can produce maximum dynamic forces of more than 1000 kN. Dynamic forces above this limit are needed, for example, in forest machines, tunneling jumbos and terminal reachstackers (Kalmar, 2021; Ponsse, 2021; Sandvik, 2021a).

The starting point for the thesis have been challenging because there are not many OEMs that can manufacture EMLAs which can produce dynamic forces of many hundreds of kilonewtons. EMLAs have a far more future than a past, so there are far less literature and research articles available than for HLAs, for example. The knowledge of the thesis is largely based on the picture provided by the OEMs, so the future research on the topic should be extended more to research articles and literature on the subject. The information is also limited because all specifications are not publicly available. Especially, the missing price information would be crucial when companies choose the most attractive product. Products from all EMLA OEMs in the world are not included in this study, so it is possible that EMLAs with better performance could exist.

In the future, it will be interesting to follow up the direction in which the trend of electrification is evolving in linear units. Will the largest linear units in the most demanding applications become heavier and heavier while maximum forces increase as the EMLA technology makes progress? The high weight of an EMLA linear unit is one of the biggest typical weaknesses compared to HLAs and is limiting the possible applications. For this reason, it would make sense to research how the weight of the linear unit of an EMLA could be reduced.

The electrification of HLAs is a broad topic, so the thesis provides only a brief overview of the subject and mainly related to MWM solutions. The design architecture of the EMLA system could be further researched in terms of compatible electric motors, gears, materials, thrust tubes, inline configuration, and accessories such as controllers, which are all only slightly discussed in this thesis. The adequacy of the EMLA technology could be also studied in a less restrictive environment, where IP rating or speed are not as significant as in outdoor MWMs, such as in different industries. In addition, the study could also be extended to consider other EMLA performance characteristics such as input torque, inertia, backlash, acceleration, positioning repeatability, and holding force of a brake.

The future research avenues may as well question, how proper will the EMLAs be compatible in the layout with zero-emission hydrogen fuel cell solutions which are suitable for high force requirements (IEA, 2019). The IEA's report (2019) on the future of hydrogen represents that the hydrogen fuel cell technology potentially begins to increase in the future heavy-duty MWMs. For example, there is preliminary cooperation in the mining sector between fuel cell technology OEM Hyzon and ITOCHU which is operating in the mining industry (Hyzon Motors, 2021).

It would be worthwhile to explore what other or perhaps even better alternatives exist for EMLAs in terms of energy efficiency and sustainable development. Norrhydro's NorrDigi is a technology that renews the design and energy efficiency of a MWM's hydraulic system. NorrDigi utilizes intelligent digital control of a multi-chamber HLA and the recovery of kinetic and potential energy with energy storage pressure accumulators. The technology overcomes some of the HLA's traditional weaknesses, so it could be a more energy-efficient or better value for money option than an EMLA, or at least an intermediate solution in some applications while EMLA technology evolves. (NorrHydro, 2021b).

REFERENCES

Al-Mashari, M.;Zairi, M. & Ginn, D. 2005. *Key enablers for the effective implementation of QFD: a critical analysis.* Industrial Management & Data Systems, Vol. 105 No. 9, pp. 1245-1260. Available: https://doi.org/10.1108/02635570510633284

Avant Tecno Oy. 2021. *Leguan. Versatile and reliable self-propelled access platforms.* Available: https://www.avanttecno.com/uk/leguan

Badrinarayanan, S.; Kumar, R; Bhinder, K.S. & Ralexander. 22-24.3.2018. *Electro mechanical linear actuator using roller screws.* IOP Conference Series: Materials Science and Engineering, Volume 402, 2nd International conference on Advances in Mechanical Engineering (ICAME 2018), Kattankulathur, India. Available: https://iopscience.iop.org/article/10.1088/1757-899X/402/1/012101

Bosch Rexroth. 2021. *Electromechanical Cylinder EMC.* Available: https://www.boschrexroth.com/en/xc/products/product-groups/linear-motion-technology/linear-axes-and-electromechanical-cylinders/electromechanical-cylinder/emc

Creative Motion Control. 2021a. *About Creative Motion Control.* Available: https://www.creativemotioncontrol.com/about-us/

Creative Motion Control. 2021b. *Electric Roller Screw Actuator Catalogs & Brochures.* Available: https://www.creativemotioncontrol.com/lp-electric-actuator-catalogs/

Creative Motion Control. 2021c. *Grooved roller thrust bearings catalogs & brochures.* Available: https://www.creativemotioncontrol.com/lp-grooved-roller-thrust-bearings/

Creative Motion Control. 2021d. *Roller screw catalogs & brochures.* Available: https://www.creativemotioncontrol.com/lp-roller-screw-catalogs/

Cudney, E. A.;& Elrod, C. C. 2011. *Quality Function Deployment in Continuous Improvement.* Available: https://www.intechopen.com/books/six-sigma-projects-and-personal-experiences/quality-function-deployment-in-continuous-improvement

Curtiss-Wright. 2021a. *FTP Series Catalog Section.* Available: https://www.cw-actuation.com/Resources/Exlar-Resources/FTP-Series-Catalog-Section

Curtiss-Wright. 2021b. *FTX Section 2021 Standard Products Catalog.* Available: https://www.cw-actuation.com/Products/Exlar-Automation/Actuators/FTX-Series

Eurostat. 2021. *Electricity price statistics*. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics#Electricity_prices_for_non-household_consumers

Ewellix. 2021a. *About us.* Available: https://www.ewellix.com/en/global/corporate/about-us

Ewellix. 2021b. *Actuator select.* Available: Cost saving calculator: https://www.ewellix.com/en/global/product-selectors/actuator-select

Ewellix. 2021c. *High performance actuator catalogue.* Available: https://medialibrary.ewellix.com/asset/16172

Ewellix. 2021d. *Linear Actuators.* Available: https://www.ewellix.com/en/global/products/linear-actuators

Festo. 2021. *Electric cylinder ESBF.* Available: https://www.festo.com/us/en/p/electric-cylinder-id_ESBF/

HYDAC. 2021. *HYDAC KineSys Electric Cylinders HEZ.* Available: https://www.hydac.com/de-en/products/motion-control-systems/electromechanic/show/Download/index.html

Hydroline. 2021a. *Customer segments - hydraulic solutions for every need.* Available: https://hydroline.fi/segments/

Hydroline. 2021b. *How to design a hydraulic cylinder?* Available: https://hydroline.fi/blog/how-to-design-a-hydraulic-cylinder/

Hydroline. 2021c. *Hydraulic cylinder manufacturing.* Available: https://hydroline.fi/our-solutions/solutions/hydraulic-cylinder-manufacturing/

Hyzon Motors. 9.11.2021. *Hyzon Motors and ITOCHU to pursue decarbonization in the global mining sector.* Available: https://hyzonmotors.com/hyzon-motors-and-itochu-to-pursue-decarbonization-in-the-global-mining-sector/

IEA. 2019. *The Future of Hydrogen.* Available: https://www.iea.org/reports/the-future-of-hydrogen

IEC. 2021. *IP Ratings.* Available: https://www.iec.ch/ip-ratings

Kalmar. 2.12.2019a. *Electric empty container handler.* Available: https://www.kalmarglobal.com/equipment-services/masted-container-handlers/electric-empty-handler-ECG70/

Kalmar. 29.4.2019b. *Kalmar continues its electrification journey with fully electric empty container handler.* Press release. Available: https://www.kalmarglobal.com/news--insights/press_releases/2019/kalmar-continues-its-electrification-journey-with-fully-electric-empty-container-handler/

Kalmar. 21.7.2021. *Kalmar Eco Reachstacker Brochure.* Guaranteed to cut costs. Available: https://www.kalmarglobal.com/equipment-services/reachstackers/eco-reachstacker/

Kollmorgen. 2021. *EC5 Series.* Available: https://www.kollmorgen.com/en-us/products/linear-actuators/electric-cylinders/ec5-series/

Lajunen, A.;Sainio, P.;Laurila, L.;Pippuri-Mäkeläinen, J.;& Tammi, K. 1.1.2018. *Overview of Powertrain Electrification and Future Scenarios for Non-Road Mobile Machinery.* Available: https://doi.org/10.3390/en11051184

Linak. 2021a. *Calculate the lifetime of your actuator.* Available: https://www.linak.com/segments/techline/tech-trends/calculate-the-lifetime-of-your-actuator/

Linak. 2021b. *How a brake works in an industrial actuator.* Available: https://www.linak.com/segments/techline/actuator-academyindustrial-actuators/how-a-brake-works-in-an-industrial-actuator/

Madu, C.N. 2020. *The House of Quality in a Minute: A Guide to Quality Function Deployment (3rd Edition)*. Charlotte, NC: Information Age Publishing. Available: https://search.ebscohost.com/login.aspx?direct=true&AuthType=cookie,ip,uid&db=e000xww&AN=2296102&site=ehost-live&scope=site

McFadden, C. 8.10.2021. *The Electrifying Story of How Sandvik Is Changing Mining Forever*. Interesting Engineering. Available: https://interestingengineering.com/the-electrifying-story-of-how-sandvik-is-changing-mining-forever

Montanhydraulik. 2021. *On- and offshore.* Available: https://montanhydraulik.com/offshore/?lang=en

Motiomax. 2021. *Motiomax Oy.* Available: https://motiomax.fi/en/motiomax-oy-en/

Nook, C. 2021. *Should You Increase RPM or the Lead of Your Lead Screw.* Helix. Available: https://www.helixlinear.com/blog/lead-screws/should-you-increase-rpm-or-the-lead-of-your-lead-screw/

Norgren. 2021. *Norgren ELION Rod-style Electric Actuators.* Available: https://www.norgren.com/uk/en/list/electric-actuators/rod-style

Norrhydro. 28.10.2020. *Perseverance Lapland-style - Norrhydro is a shining example of the industrial expertise of the North.* Blog. Available: https://www.norrhydro.com/blog/perseverance-lapland-style-norrhydro-is-a-shining-example-of-the-industrial-expertise-of-the-north

Norrhydro. 2021a. *High-quality hydraulic cylinders.* Available: https://www.norrhydro.com/en/hydraulic-cylinders

NorrHydro. 2021b. *NorrDigi for the green future.* Available: https://www.norrhydro.com/en/norrhydro-product-brochures

Parker. 2021. *Electric Cylinders.* Available: http://www.parkermotion.com/products/Electric_Cylinders__7317__30_32_80_567_29.html

Ponsse. 2021. *Beaver.* Available: https://www.ponsse.com/fi/tuotteet/harvesterit/tuote/-/p/beaver#/

Power Jacks. 2020. *Rolaram. Rolaram Linear Actuator.* Available: https://www.powerjacks.com/products/electric-linear-actuators/rolaram

Royal Cylinders. 2021a. *About us.* Available: http://royalcylinders.com/about.php

Royal Cylinders. 2021b. *Electric cylinder.* Available: https://royalcylinders.com/e-series-page.php

Sandvik. 2021a. *DT621 Tunneling Jumbo.* Available: https://www.rocktechnology.sandvik/en/products/underground-drill-rigs-and-bolters/tunneling-jumbos/dt621-tunneling-jumbo/

Sandvik. 8.9.2021b. *The mine of the future is electric.* Available: https://www.home.sandvik/en/stories/articles/2021/09/the-mine-of-the-future-is-electric/

Shelton, G. 10.6.2010. *Roller Screw Actuators: Benefits, Selection and Maintenance.* Exlar Resources. Available: https://www.cw-actuation.com/Resources/Exlar-Resources/Roller-Screw-Actuators-Benefits,-Selection-and-Mai

SKF. 2017. *High Performance Actuator Catalogue.* http://www.ermec.com/catalogos/2017/High%20performance%20actuator%20catalogue%20(HPA)%20-Actuador%20lineal%20de%20alto%20rendimiento%20SKF%20ERMEC.pdf

SKF. 2021. *Bearing basics.* Available: https://www.skf.com/group/products/rolling-bearings/principles-of-rolling-bearing-selection/general-bearing-knowledge/bearing-basics

Thomas Publishing Company. 9.11.2021. *Complete Guide to Actuators* (Types, Attributes, Applications and Suppliers). Available: https://www.thomasnet.com/articles/pumps-valves-accessories/types-of-actuators/#actuator_definition

Thomson. 2021a. *Electrak HD Linear Actuators.* Available: https://www.thomsonlinear.com/en/products/linear-actuators/electrak-hd#literature

Thomson. 2021b. *Why is anti-rotation required.* Available: https://www.thomsonlinear.com/en/support/tips/why-is-anti-rotation-required

Tolomatic. 2017. *Actuator Life: How to estimate for ball and roller screw actuators.* Available: https://www.tolomatic.com/info-center/resource-details/actuator-life-how-to-estimate-for-ball-roller-screw-actuators

Tolomatic. 2021a. *About us.* Available: https://www.tolomatic.com/about-us

Tolomatic. 2021b. *Electric actuators for hydraulic replacement.* Available: https://info.tolomatic.com/e-book-electric-linear-actuators-for-hydraulic-replacement

Tolomatic. 2021c. *RSX Extreme Force Linear Actuators.* Available: https://www.tolomatic.com/products/product-details/rsx-extreme-force-electric-linear-actuators

Tolomatic. 2021d. *Tolomatic Electric Actuator Sizing Application.* Available: http://sizeit.tolomatic.com/

Volvo Construction Equipment. 2017. *Volvo CE unveils 100 % electric compact excavator prototype.* Available: https://www.volvoce.com/global/en/this-is-volvo-ce/what-we-believe-in/innovation/prototype-electric-excavator/

Yanmar. 10.4.2019. *Yanmar Unveils its Exciting New eFuzion Concept at bauma.* Available: https://www.yanmar.com/global/construction/news/2019/04/10/53748.html