LEGaTO

Low Energy Toolset for Heterogeneous Computing

D5.4 "Report on evaluation of efficiency and TCO improvements of use cases"

Version 1.1

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Change Log

Version	Description of Change
V 0.1	Initial structure
V 0.2	Initial description of the Smart City Use case
V 0.3	Initial integration of all use cases
V 0.4	Added executive summary
V 0.5	Added conclusions
V0.6	UBI and BSC TCO tables format unified
V1.0	Initial draft for internal review
V1.1	Improved consistency across the document. Added clarifications.

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1. Executive Summary

To assess the impact on the use cases, we have evaluated and compared performance and energy-efficiency gains, alongside Total Cost of Ownership (TCO) savings achieved by using LEGaTO technology. The analysis included various TCO optimisation factors as, e.g., the reduction of space, the energy consumption required at the data centre, or the costs for migration, operation, and upgrade. TCO calculations and comparisons have been performed for all the LEGaTO use cases. TCO analysis is based on the LEGaTO hardware costs, system efficiency improvements, middleware installation cost and improvements, and application performance and efficiency. Many different metrics as input data have been assessed, and a reasonable set has been extracted as a basis for the TCO calculation. Then, two different scenarios have been considered, (i) where a hardware upgrade of servers after the first 3-5 years of operation is considered and (ii) where no hardware upgrade is considered.

The use case TCO calculations were computed on LEGaTO hardware (details are given in each use case subsection), based on a comparison against unoptimised hardware baselines. The smart home baseline is a workstation with an Intel i7-7700K @ 4.2 GHz, 32 GB RAM and 2x Nvidia GeForce 1080TI. For the smart city use case, the baseline is 1 node of Marenostrum supercomputer (2x Intel Xeon Platinum 8160 24 cores at 2.1 GHz and 12x8 GB DDR4-2667 DIMMS, 2GB/core). The Infection Research (Healthcare) use case is a workflow composed of multiple application stages; for this reason, there are three baselines corresponding to the distinct stages utilising an Intel E3-1505Mv6 (4 cores), Intel D-1577 (16 cores) and Intel E-2176M CPU (6 Cores) all with 32 GB RAM. Machine Learning baseline uses an Nvidia Xavier for the edge case and Nvidia GeForce 2060 RTX for the cloud case. For TCO, we have the following improvements for each use case: On the Smart Home use case, the use of LEGaTO hardware and the OmpSs@Cluster toolset led to a TCO decrease of 81.6%. On the Smart City use case, adapting Alya to run on the Nvidia AGX Xavier boards provided reductions on the TCO of about 70%. On the Infection Research use case, we achieved a large TCO reduction of from 91.8% to 98.8% through the use of optimised LEGaTO hardware and software. For Machine Learning use case, TCO savings of 43.8% was achieved through leveraging energy-efficient Neural Network optimisations. Finally, for the software-based Secure IOT Gateway use case, TCO reduction was up to 40%. The difference in TCO improvements across the different use cases is explained in detail in this document. In general, this is because of the different optimisation levels at project start, i.e., some use cases were more optimised than others at project start. This deliverable is public and, therefore, it does not include business information that is considered confidential by the LEGaTO consortium such as exact or absolute pricing of hardware components.

2. Introduction

Workpackage 5 was focused on using tools and methods developed in WP2, WP3, and WP4 to characterise, evaluate and optimise the LEGaTO use cases with optimised TCO. This document is the output of Task 5.7 on the use of LEGaTO stack. We assessed the performance gain with a focus on energy- and cost-savings, estimating the impact of the appliances for data centres or edge devices. This task calculated server costs based on the given configuration, estimation of energy consumption for given workloads and predicted costs (replacement, operations, upgrades, etc.).

This document includes the methodology for TCO calculation and its relevance in the context of the use cases in this project. It is followed by the TCO-related work in LEGaTO, the breakdown of costs of the LEGaTO stack, and the analysis of TCO based on the different LEGaTO use cases. The TCO estimation for the baseline and the preconfigured appliances is presented based on measured real data. These results are discussed based on tables that compare the price of standard servers with the LEGaTO hardware.

3. Methodology

In the following section, we discuss the procedure to build the TCO tables presented in this document. The LEGaTO data was collected by running the use cases considered in WP5, which were embedded and optimised using the LEGaTO hardware/software ecosystem. This document collects the values for multiple metrics, as shown in Tables 1 and 2. Some of the hardware performance/efficiency data for the standard infrastructure options were taken from estimations. Table 1 is related to the upfront hardware costs, and Table 2 is about software/hardware deployment, running and maintenance cost.

Item	Metric	Description
Server Unit RAM	GB	The size of RAM memory per node
Server Unit CPU Cores	# of cores	The number of CPU cores per node
Number of Server Units	# of servers	Number of servers including basic Infrastructure like switches
Number of GPUs	# of GPUs	Number of GPUs
Number of FPGAs	# of FPGAs	Number of FPGAs
Total number of chassis	Chassis	Total chassis number
Overall Space occupation	In RU	Overall space utilisation in terms of Rack Units
Overall hardware cost	EUR	Overall hardware cost of the system
Performance /Node	Perf	Number of operations (in terms of frames/sec or FLOPS) per node
Power Consumption	Watts	Power dissipation
Performance of HW	Perf/Sec	Number of operations/second

Table 1: Description of upfront hardware information used on the TCO tables

Item	Metric	Description
Energy Efficiency	Perf/Joule	Number of operations/energy
PUE	Constant	Power Usage Effectiveness (Total energy / IT equipment energy)
Average server power dissipation	Watts	Average power dissipation of server
Electricity cost 1 kWh	EUR	Electricity cost per kilowatt hour
Server HW	EUR	Cost of server hardware
Installation and integration Of HW and SW up to OS	EUR	System firmware and hardware setup costs
Application software installation	EUR	Application software setup costs
Network (HW and SW)	EUR	The costs of the usage of the network by hardware and software
Operation	EUR	Costs of the maintenance of the IT system, including hardware maintenance such as disks, ram, etc.
Migration	EUR	Costs of migration the use case to the LEGaTO hardware
Electricity	EUR	Overall costs for electricity consumption
Space costs	EUR	Data centre (DC) costs (floor space and DC equipment, e.g. racks, PDUs, etc.)
Upgrade	EUR	Expenses in further upgrade after 3/5 years
Total cost	EUR	Global system costs

Table 2: Description of the fields used for denoting installation, running and maintenance costs on the TCO tables

This TCO analysis focuses on hardware costs and energy consumption. Therefore, it is not a complete TCO analysis, which would typically include the following as well:

- The costs for "Warranties and licenses".
- The more general fields like "Audit", "Insurance" or "Decommission" were excluded as they are hard to quantify, often depending on a multitude of choices, as well as being dependent of the existing infrastructure.
- The staff costs of IT personnel are distributed throughout the different tasks where relevant.

A profit margin is added to each hardware component. Commercially available off-the-shelf hardware which is included (e.g. GPUs, FPGAs) are calculated with a low profit margin, being easily comparable with other distributors in the market. On the other hand, the LEGaTO hardware components (e.g. chassis and microservers) are considered with a reasonable profit margin to cover not only production and mechanical assembly costs but also a small overhead for the installation of the middleware and OS on the microservers.

It should be noted that the rows in the Tables 1 and 2 are different in terms of significance for the two broad application areas that are considered for the use cases: the Cloud/HPC/Data Centre and edge/embedded/IoT. For example, the Smart Mirror in the Smart Home use case is installed in a domestic environment, typical of an edge/IoT deployment; and therefore the electrical energy cost is higher than that for a data centre.

4. Smart Home Use case

The Smart Home Use case is centred around using the developed embedded edge server instead of conventional workstation hardware. As the centrepiece of a smart home environment, a smart mirror is chosen for this TCO analysis. A detailed description can be found in Deliverable 5.3, chapter 3. The smart mirror is installed in a domestic environment and therefore does not contain some of the costs that would incur in a data centre environment. In addition, the costs for electrical energy are calculated at a higher rate compared to data centres. Also, upgrade costs, space and migration are assumed zero, as this is not applicable for an IoT application (see Section 2.)

4.1. Baseline Workstation TCO

At the start of the project, a smart mirror prototype was created based on conventional workstation hardware. The resulting TCO table describing this case is shown in Figure 1. The described system consists of a workstation with an Intel i7-7700K @ 4.2 GHz, 32 GB RAM and 2x Nvidia GeForce 1080TI. It performed at 16 FPS with a power consumption of 650 W after the first optimisations were concluded. In this case, the energy costs are the most significant part with a cost of 23 cents per kW, which totals to 4 € per day, if the mirror is operated continuously over the full day. The initial hardware cost is also comparably small with 2.840 € to the energy costs after 10 years of use under complete load, totalling around 15.715 €.

LEGaTO Use Case Smart Home, Standard-Hardware, Non-Optimised Software

Total cost of ownership (TCO) is an analysis that places a single value on the complete lifecycle of a capital purchase.

Standard Workstation Hardware:
Intel Core i7-7700K CPU @ 4.20GHz
64 GB RAM
2x Gigabyte GeForce 1080 Ti

* If placed in a data center, but irrelevant here

Hardware costs			costs/unit	overall costs
Workstation unit RAM	32	GB RAM		
Workstation unit CPU cores	8	CPU cores		
Number of server units	1	nodes	1.420,00€	1.420,00€
Number of GPUs	2	GPUs	710,00€	1.420,00€
Number of FPGAs	0	FPGAs	0,00€	0,00€
Total number of chassis	1	Chassis		
Overall space occupation	4	RU*		
Overall hardware cost				**2.840,00€**
Performance / node	16,00			
power consumption [W]	650,00			
Total space in U	4,00			

Energy efficiency		metrics
Performance of above hardware	16,00	Frames / Sec
Energy efficiency	0,02	Frames / Joule

Electricity costs		day	month	year	
PuE (constant)	1,20				
Average server power consumption (W)	650	18,7	561,6	6832,8	
electricity cost 1kWh (EUR)	0,23	4	129	**1572**	Yearly electricity costs

Other costs		Usage period		Year									
Items	Costs	(years)	Invest	1	2	3	4	5	6	7	8	9	10
Server Hardware	2.840,00€	10	2.840,00€	2.840,00€	2.840,00€	2.840,00€	2.840,00€	2.840,00€	2.840,00€	2.840,00€	2.840,00€	2.840,00€	2.840,00€
Installation and integration of hardware and software up to OS	150,00€	10	150,00€	150,00€	150,00€	150,00€	150,00€	150,00€	150,00€	150,00€	150,00€	150,00€	150,00€
Application software installation	0,00€	10	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€
Network (hardware and software)	100,00€	10	100,00€	100,00€	100,00€	100,00€	100,00€	100,00€	100,00€	100,00€	100,00€	100,00€	100,00€
Operation/Maintenance	50,00€	1	0,00€	50,00€	100,00€	150,00€	200,00€	250,00€	300,00€	350,00€	400,00€	450,00€	500,00€
Migration	0,00€	10	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€
Electricity	1.571,54€	1	0,00€	1.571,54€	3.143,09€	4.714,63€	6.286,18€	7.857,72€	9.429,26€	11.000,81€	12.572,35€	14.143,90€	15.715,44€
Space costs	0,00€	1	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€
Upgrade	0,00€	3	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€
total cost			**3.090,00€**	**4.711,54€**	**6.333,09€**	**7.954,63€**	**9.576,18€**	**11.197,72€**	**12.819,26€**	**14.440,81€**	**16.062,35€**	**17.683,90€**	**19.305,44€**

Figure 1: TCO Table for the Smart Mirror Use case prototype on a conventional workstation hardware

4.2. Embedded edge Server TCO

With the introduction of efficient embedded hardware, the energy costs are reduced drastically from 650 W down to 55 W. This is shown in Figure 2. The hardware, in this case, is the LEGaTO edge server with two Nvidia Xavier modules. In order to be able to use all hardware parts, OmpSs@Cluster was used to migrate calculations of some neural networks to the second Xavier. The test setup has shown a performance of 16 FPS with a total power consumption of 55 W.

Thereby, it shows the same performance as the first setup after the first optimisation and can therefore be easily compared. The initial buying costs are also lower than two high-end GPUs and a high-end CPU with around 1.805 €, and they are more substantial to the total cost after 10 years compared to the energy cost. The energy costs are down to 36 cents per day and a yearly cost of 132.98 €. After 10 years the total cost of ownership is down to 3,884.77 €

LEGaTO Use Case Smart Home, LEGaTO-Hardware, Optimised Software														
Total cost of ownership (TCO) is an analysis that places a single value on the complete lifecycle of a capital purchase.														
Hardware costs			Costs / unit	Overall costs										
Microserver RAM	32	GB RAM												
Microserver CPU cores	16	CPU cores												
Number of Microservers	2	nodes	728,00€	1.456,00€										
Number of GPUs	0	GPUs	0,00€	0,00€										
Number of FPGAs	0	FPGAs	0,00€	0,00€										
Overall space occupation	2	RU*												
Overall hardware cost				**1.456,00€**										
Performance / node	16													
power consumption [W]	55													
Total space in U	2													
Energy efficiency		metrics												
Performance of above hardware	16,00	Frames / Sec												
Energy efficiency	0,29	Perf / Joule	**gain:**	1081,82 %										
Electricity costs		**day**	**month**	**year**										
PuE (constant)	1,20													
Average server power consumption (W)	55,00	1,6	48	578										
electricity cost 1kWh (EUR)	0,23	0,36€	10,93€	**132,98€**	Yearly electricity costs									
		Usage period			Year									
Other costs	Costs	(years)	Invest	1	2	3	4	5	6	7	8	9	10	
Server Hardware	1.456,00€	10	1.456,00€	1.456,00€	1.456,00€	1.456,00€	1.456,00€	1.456,00€	1.456,00€	1.456,00€	1.456,00€	1.456,00€	1.456,00€	
Installation and integration of hardware and software up to OS	150,00€	10	150,00€	150,00€	150,00€	150,00€	150,00€	150,00€	150,00€	150,00€	150,00€	150,00€	150,00€	
Application software installation	0,00€	10	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	
Network (hardware and software)	100,00€	10	100,00€	100,00€	100,00€	100,00€	100,00€	100,00€	100,00€	100,00€	100,00€	100,00€	100,00€	
Operation	50,00€	1	0,00€	50,00€	100,00€	150,00€	200,00€	250,00€	300,00€	350,00€	400,00€	450,00€	500,00€	
Migration	0,00€	10	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	
Electricity	132,98€	1	0,00€	132,98€	265,95€	398,93€	531,91€	664,88€	797,86€	930,84€	1.063,81€	1.196,79€	1.329,77€	
Space costs	0,00€	1	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	
Upgrade	0,00€	3	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	
Total Cost			**1.706,00€**	**1.888,98€**	**2.071,95€**	**2.254,93€**	**2.437,91€**	**2.620,88€**	**2.803,86€**	**2.986,84€**	**3.169,81€**	**3.352,79€**	**3.535,77€**	

Edge Server Hardware:
t.recs edge Server
2x Nvidia AGX Xavier

* If placed in a data center, but irrelevant here

Figure 2: TCO Table for the embedded hardware setup for the Smart Home Use case.

4.3. Conclusion

Due to the usage of efficient specialised hardware, the energy consumption can be decreased significantly. The daily energy cost is decreased from 4 € to 0.36 €, which accumulates to a decrease from 1572 € to 132.98 €. By itself, this is a reduction of 91.5 % (factor 11.8). The hardware costs are also reduced from 2.840 € for a high-end workstation to 1805 € for an edge server with two Nvidia Xavier modules, which is a reduction of 36.4% (factor 1.6).

Energy costs and hardware acquisition are the two most significant factors in this edge use case because the hardware is designed for home usage and not for the data centre. We achieved an overall TCO improvement of 81% for the smart mirror prototype with these two optimisations.

5. Smart City use case

We have used the Alya application [5] developed at BSC, in order to determine the benefits of migrating its execution from the Marenostrum IV Supercomputer [2] to a LEGaTO-based data centre. In this section, we describe the two Alya versions used for the evaluation of the Total Cost of Ownership (TCO), the hardware selected for the assessment, the baseline TCO obtained in Marenostrum, and the TCO with several execution modes of the LEGaTO hardware.

5.1. Platforms description

In this section, we describe the two different hardware platforms that are compared.

5.1.1. Marenostrum

We used one node of the Marenostrum IV supercomputer to compute the baseline of the TCO. It consists of two Intel Xeon Platinum 8160 processors, with 24 cores each, and hyperthreading disabled, running at 2.10 GHz. Each processor has a Thermal Design Power (TDP) of 150 W. The node has 96 GB of main memory, having 12 DIMM of 8 GB, clocked at 2667 Mhz.

5.1.2. Nvidia Jetson Xavier AGX

The Nvidia Jetson Xavier AGX system is a microserver that has as a custom Carmel ARMv8.2-A (64-bit) CPU with 8 cores, and a Volta-based GPU with 512 CUDA cores. The CPU runs at frequencies ranging from 1.377 GHz to 2.3 GHz, and the GPU frequency ranges from 0.854 to 1.377 GHz. The chip has a TDP of 30W. The Nvidia Xavier board has 32GB of LPDDR4 memory and an Ethernet network connection configurable to 1 and 10 Gbit.

The system can be run in different power modes, depending on what the objective is. There are 8 different power modes using different computing parts at different frequencies. But after some analysis, we only saw the need to use 2 different modes, the one at maximum power usage, and another one capped at 30W, retaining the maximum number of processors of both the CPU and GPU cores, while lowering the frequency to the lowest possible value.

This will allow us to keep our computing capabilities in the system but greatly reduce the power consumption, as frequency has a much higher impact on power consumption than the number of active processing units.

5.2. Description of the software versions

Parallel Alya in Marenostrum. The baseline version is based on the execution of the MPI version in one node of Marenostrum-IV with 48 MPI processes, thus filling all CPU cores, since it has two processors with 24 cores each, as noted in section 4.1.1.

Heterogeneous Alya in Nvidia Xavier. The execution on the Nvidia Xavier node is based on the GPU version of the Alya code. It is run with 4 MPI processes, all of them offloading work to the node embedded GPU.

5.3. Baseline TCO on Marenostrum

To calculate the TCO on Marenostrum, we have executed Alya with 48 cores on one node and determined the total number of FLOPs (floating-point operations), execution time, power consumption and the market price of the Marenostrum node. From those values, we get the TCO using the spreadsheet shown in Figure 3.

For the 1st year, it results in an investment of 12,064.41 €, and those are increased yearly by 1,244 € due to electricity costs, and around 14,000 € every 4 years, when including the renewal of the equipment. After 10 years, the final cost is 70,378.43 €.

5.4. Baseline TCO on Nvidia Jetson Xavier AGX

In order to accomplish the TCO on the Nvidia Xavier AGX system, we executed Alya with the 8 cores and GPU, and calculated its power consumption through the use of the tool tegrastats [3].

Unfortunately, we didn't have the tools needed to extract the total number of FLOPs, but we used the measured number from Marenostrum in order to get FLOP/s, since, in theory, the amount of floating-point operations is determined by the use case in the ported part of the solver.

We also performed 4 different executions, one at full power usage (power mode 0), and one power mode capped at 30W (power mode 3), while using just one Xavier node, or two.

In both cases tested with only 1 Xavier board, the initial investment is 3,100.00 €, and with 2 boards, 4,200.00 €. Since setting the system up is so easy, we have considered the cost of this 0 €. So we are only adding the cost of the extra microserver.

The results accomplished are as follow:

- 1 Xavier power mode 0: We achieved an energy efficiency gain of 460% relative to the baseline Marenostrum case, and the results of investment are increments of approximately 23 €/year in electricity costs. At the end of the 10-year period, the total cost has been up to 14,081.77 €.
- 1 Xavier power mode 3: For this power mode, we got an energy efficiency gain of 702 %, the biggest value. The yearly cost of electricity is 9 €/year, and at the end of the 10-year period the money spent adds up to 13,940.88 €.
- 2 Xavier power mode 0: In this case, the power efficiency goes down to 317 %. And the estimated electricity cost is 44.52 €/year. At the end of the 10-year period, the estimated cost is 19,245.19 €.
- 2 Xavier power mode 3: The last configuration has an energy efficiency of 452% (which is more or less similar to that of just one Xavier board). The yearly electricity cost is 21.15 €. And at the end of the period, the total cost is 19,011.46€.

5.5. Conclusions

We achieved significant improvements in energy efficiency through the usage of CUDA and the Nvidia Jetson Xavier AGX board. We tested different settings and the best in energy efficiency, and total costs are with the 1 Xavier with power mode 3. In this particular case, the improvements over

the baseline in Marenostrum are about 450% on energy efficiency and a reduction on the TCO of 70%.

Unfortunately, we couldn't achieve better energy efficiency with 2 or more board settings since the communication part of the software is essential for the execution time. Since the boards use a network connection over PCIe, there's a lot of waiting involved for the ported part of the system (it is the most communication-bounded part of the software). Therefore, even better execution time and energy efficiency would be achieved through the usage of faster networking access.

LEGaTO Use Case Smart City, Standard-Hardware, Non-Optimised Software

Total cost of ownership (TCO) is an analysis that places a single value on the complete lifecycle of a capital purchase.

Standard node hardware:
Intel(R) Xeon(R) Platinum 8160 CPU @2.10GHz
96 GB RAM
Intel(R) Omni-Path(R) Interface Adapter 100 Series

Hardware costs			costs/unit	overall costs
Server unit RAM	96	GB RAM		
Server unit CPU cores	24	CPU cores		
Number of server units	1	nodes	10.064,41€	10.064,41€
Number of GPUs	0	GPUs	0,00€	0,00€
Number of FPGAs	0	FPGAs	0,00€	0,00€
Total number of chassis	1	Chassis		
Overall space occupation	5	RU		
Overall hardware cost				**10.064,41€**
Performance / node	5,45E+10	FLOPS		
power consumption [W]	946,62			
Total space in U	1,50			

Marenostrum costs

	Node	Unit cost	Total
cpu	2	4.018,80	8.037,61
board	1	1.500,00	1.500,00
memory	12	43,90	526,80
		Total	**10.064,41 €**

Energy efficiency		metrics
Performance of above hardware	5,45E+10	Perf / Sec
Energy efficiency	5,75E+07	Perf / Joule

Electricity costs		day	month	year	
PUE (constant)	1,5				
Average server power consumption (W)	946,6	34,1	1022,4	12438,6	
electricity cost 1kWh (EUR)	0,1	3	102	**1.243,86 €**	Yearly electricity costs

Other costs		Usage period						Year					
Items	Costs	(years)	Invest	1	2	3	4	5	6	7	8	9	10
Server Hardware	10.064,41€	10	10.064,41€	10.064,41€	10.064,41€	10.064,41€	10.064,41€	10.064,41€	10.064,41€	10.064,41€	10.064,41€	10.064,41€	10.064,41€
Installation and integration of hardware and software up to OS	1.000,00€	3	1.000,00€	1.000,00€	1.000,00€	1.000,00€	2.000,00€	2.000,00€	2.000,00€	3.000,00€	3.000,00€	3.000,00€	4.000,00€
Application software installation	500,00€	3	500,00€	500,00€	500,00€	500,00€	1.000,00€	1.000,00€	1.000,00€	1.500,00€	1.500,00€	1.500,00€	2.000,00€
Network (hardware and software)	500,00€	10	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€
Operation	503,22€	1	0,00€	503,22€	1.006,44€	1.509,66€	2.012,88€	2.516,10€	3.019,32€	3.522,54€	4.025,76€	4.528,98€	5.032,20€
Migration	0,00€	10	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€
Electricity	1.243,86€	1	0,00€	1.243,86€	2.487,72€	3.731,58€	4.975,44€	6.219,30€	7.463,16€	8.707,02€	9.950,88€	11.194,74€	12.438,60€
Space costs	375,00€	1	0,00€	375,00€	750,00€	1.125,00€	1.500,00€	1.875,00€	2.250,00€	2.625,00€	3.000,00€	3.375,00€	3.750,00€
Upgrade	10.864,41€	3	0,00€	0,00€	0,00€	0,00€	10.864,41€	10.864,41€	10.864,41€	21.728,81€	21.728,81€	21.728,81€	32.593,22€
total cost			**12.064,41€**	**14.186,49€**	**16.308,57€**	**18.430,65€**	**32.917,14€**	**35.039,22€**	**37.161,30€**	**51.647,79€**	**53.769,87€**	**55.891,95€**	**70.378,43€**

Figure 3: TCO Table for a node of Marenostrum IV running the Smart City use case

LEGaTO Use Case Smart City, LEGaTO-Hardware, Optimised Software

Total cost of ownership (TCO) is an analysis that places a single value on the complete lifecycle of a capital purchase.

Edge Server Hardware:
t.recs edge Server
2x Nvidia AGX Xavier

Hardware costs			Costs / unit	Overall costs
Microserver RAM	16	GB RAM		
Microserver CPU cores	8	CPU cores		
Number of Microservers	2	nodes	1.100,00€	2.200,00€
Number of GPUs	2	GPUs	0,00€	0,00€
Number of FPGAs	0	FPGAs	0,00€	0,00€
Total number of M2DC Server Barebones	0	Barebones	0,00€	0,00€
Overall space occupation	0	RU		
Overall hardware cost				**2.200,00€**
Performance / node	3,83E+09	FLOPS		
power consumption [W]	12,07			
Total space in U	2,00			

Energy efficiency		metrics		
Performance of above hardware	7,66E+09	Perf / Sec		
Energy efficiency	3,17E+08	Perf / Joule	**gain:**	451,57 %

Electricity costs		day	month	year	
PUE (constant)	1				
Average server power consumption (W)	24,1	0,6	17	211	
electricity cost 1kWh (EUR)	0,1	0,06€	1,74€	**21,15€**	Yearly electricity costs

Other costs		Usage period						Year					
	Costs	(years)	Invest	1	2	3	4	5	6	7	8	9	10
Server Hardware	2.200,00€	10	2.200,00€	2.200,00€	2.200,00€	2.200,00€	2.200,00€	2.200,00€	2.200,00€	2.200,00€	2.200,00€	2.200,00€	2.200,00€
Installation and integration of hardware and software up to OS	1.000,00€	3	1.000,00€	1.000,00€	1.000,00€	1.000,00€	2.000,00€	2.000,00€	2.000,00€	3.000,00€	3.000,00€	3.000,00€	4.000,00€
Application software installation	500,00€	3	500,00€	500,00€	500,00€	500,00€	1.000,00€	1.000,00€	1.000,00€	1.500,00€	1.500,00€	1.500,00€	2.000,00€
Network (hardware and software)	500,00€	10	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€
Operation	110,00€	1	0,00€	110,00€	220,00€	330,00€	440,00€	550,00€	660,00€	770,00€	880,00€	990,00€	1.100,00€
Migration	0,00€	10	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€
Electricity	21,15€	1	0,00€	21,15€	42,29€	63,44€	84,58€	105,73€	126,87€	148,02€	169,16€	190,31€	211,46€
Space costs	0,00€	1	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€
Upgrade	3.000,00€	3	0,00€	0,00€	0,00€	0,00€	3.000,00€	3.000,00€	3.000,00€	6.000,00€	6.000,00€	6.000,00€	9.000,00€
Total Cost			**4.200,00€**	**4.331,15€**	**4.462,29€**	**4.593,44€**	**9.224,58€**	**9.355,73€**	**9.486,87€**	**14.118,02€**	**14.249,16€**	**14.380,31€**	**19.011,46€**

Figure 4: TCO Table for a prototype consisting of two Nvidia Xavier boards running the Smart City use case at low-power mode 3

6. Infection Research use case

In this section, the TCO analysis of three individual steps of a new biomarker discovery workflow will be presented. The complete biomarker discovery workflow is described in detail in the deliverable D5.3 [5]. The workflow consists of separate steps, which were developed independently.

The following TCO analysis deals with the cost of the optimised versions for the simulations of biomarker candidates (Figure 6), the selection of a subset of biomarker candidates using tree based methods (Figure 7) and the calculation of the classifier performance (Figure 8) using combinations of biomarker candidates as opposed to standard versions with standard calculations. For the simulations of biomarker candidates (Figure 6), not only optimised software, but also optimised hardware is considered. The proof of concept with OmpSs@FPGA to accelerate a transformation using an FPGA development ZedBoard [4] is listed in terms of computation time and energy efficiency, but not in terms of total cost of ownership (Figure 5).

For each of the other three parts of the biomarker discovery workflow two scenarios are listed. We estimated the amount of hardware that would be required to achieve the same total performance as the optimised version using the standard software and an x86 processor. To calculate our estimates, we multiplied the baseline for the standard version with the acceleration factor of the optimised version. We assume that our systems are running nonstop for 10 years. After 5 years we estimated an hardware update for the CPUs and FPGAs.

Acceleration is a key factor in in analysing larger datasets. Using the standard versions we were not able to handle datasets in that dimension before. It was previously impossible to achieve a result in a reasonable time. Now we can process new dimensions of data, and the resulting benefits for further biomarker research are unpredictable. For example, as we see in the current pandemic, understanding infections, developing new drugs, and monitoring disease progression are of great importance. In addition, if calculations take a long time, personnel costs increase, and research is delayed.

The optimised version for the simulations of biomarker candidates (Figure 6) not only uses an optimised software of the cut index functionality re-implemented in Maxeler's MaxJ language and compiled to a state-of-the-art MAX5 DFE card with MaxCompiler, but also a state-of-the-art MAX5 DFE card instead of CPUs. So the first part was compared with a standard R software version running on a Microserver equipped with an Intel E3-1505M v6 CPU with 4 cores, 32 GB RAM and an optimised version running on optimised hardware, a state-of-the-art MAX5 DFE card.

The second and third part, the selection of a subset of biomarker candidates using tree-based methods based on results of the simulations of biomarker candidates (Figure 7) and the calculation of the classifier performances (Figure 8), were compared using the same hardware. The measurements for the comparison of the optimised and the standard version of the subset selection (Figure 7) were carried out on a Microserver equipped with an Intel D-1577 CPU with 16 cores and 32 GB RAM. The acceleration of the optimised version is based on including the results of the simulations and thus aborting unpromising trials of the hyperparameter optimisation early.

The calculation of the classifier performances (Figure 8), was compared using a Microserver equipped with an Intel E-2176M CPU with 6 Cores and 32 GB RAM. The standard version is implemented in Python and the optimised version is re-implemented in C++ and parallelised using

XiTAO. Both versions ran in parallel with 12 threads. Identical hyperparameters and the same algorithm were used in each case. 15504 combinations were calculated.

As Figure 5 indicates, the optimised transformation and the optimised calculation of the classifier performance application parts dissipate more power per unit of time compared to their unoptimised parts due to the more intense use of the hardware due to optimisations. However, these optimised application parts run more efficiently accomplishing much more work completed per unit of energy (for example 3.28 and 1350.11 combinations/kJ in the classifier part for baseline and optimised results respectively).

The total cost of ownership for calculating 5 million simulations is relatively reduced by 97.1%. For the first 97 trials during a hyperparameter optimisation to select the subset of biomarker candidates, the total cost of ownership can be reduced by 91.8%. For this calculation, a data set connected to hip infections with 50416 biomarker candidates was analysed. Finally, the calculation of the classifier performance in our example data set has an estimated total cost of ownership reduction of 98.8%.

All calculations are subject to random effects due to the nature of the algorithm. One measurement for each application part was carried out and reported. The listed results only apply to the respective specific sample data set described in the deliverable D5.3 [5].

LEGaTO Use Case Infection Research							
Total cost of ownership (TCO) is an analysis that places a single value on the complete lifecycle of a capital purchase.							
Hardware costs Cloud Server		**amount**	**costs/unit**	**overall costs**			
Microserver Intel E3-1505M v6, 4 Cores, 32 GB RAM		9	879.00 €	7.911.00 €			
Microserver Intel E-2176M, 6 Cores, 32 GB RAM		9	919.00 €	8.271.00 €			
Microserver Intel D-1577, 16 Cores, 32 GB RAM		6	2.898.00 €	17.388.00 €			
Maxeler DFE (FPGA PCIe card)		1	8.000.00 €	8.000.00 €			
RECS|Box Deneb Barebone		1	21.094.00 €	21.094.00 €			
Overall space occupation (RU, Rack Units)		3					
Example hardware cost				**62.664.00€**			
Hardware costs FPGA Prototype Board		**amount**	**costs/unit**	**overall costs**	**typical power**	**total power**	
FPGA - ZedBoard XILINX	1	FPGA	380.00€	380.00€	4	4	
	Total runtime for specific dataset (seconds)						
Application part	**Baseline**	**Optimization**	**Improvement**				
Simulations (5 million)	13990.0	5.6	2.503.58 x				
Transformation (proof of concept)	10.9	1.2	9.47 x				
Biomarker Subset Selection	259200.0	6407.1	40.45 x				
Classifier	104992.0	193.0	544.00 x				
	Average Energy Consumption (Watt)		**Yearly Electricity Costs**			PuE = 1,2	
Application part	**Baseline**	**Optimization**	**Baseline**	**Optimization**	**Improvement**	Electricity Costs: 1kWh=0,25 €	
Simulations	64.8	21.0	**170.29 €**	**55.19 €**	3.09 x		
Transformation (proof of concept)	4.0	4.5	**10.51 €**	**11.83 €**	0.89 x		
Biomarker Subset Selection	31.3	31.3	**82.20 €**	**82.20 €**	1.00 x		
Classifier	45.0	59.5	**118.26 €**	**156.37 €**	0.76 x		
	Energy Efficency						
Application part	**Baseline**	**Optimization**	**Improvement**				
Simulations (simulations/J)	5.52	59523.80	10.783.30 x				
Transformation (transformations/J)	1159.59	9691.66	8.36 x				
Biomarker Subset Selection (trials/kJ)	0.01	0.48	40.45 x				
Classifier (combinations/kJ)	3.28	1350.11	411.43 x				

Figure 5: Summary of hardware and applications used in the Infection Research use case.

Simulations, Standard Version (R language)		Hardware Setup: 31x RECS|Box Deneb Barebone + 833x Microserver Intel E3-1505M v6											
Other costs		Usage period					Year						
Items	Costs	(years)	Invest	1	2	3	4	5	6	7	8	9	10
Number of Microservers per Chassis	27												
Total number of Chassis	31												
Total number of Microservers	833												
Hardware costs per Chassis	44.827.00€												
Total hardware costs	1.383.549.38€	Some parts 5, some 10	1.383.549.38€	1.383.549.38€	1.383.549.38€	1.383.549.38€	1.383.549.38€	1.383.549.38€	2.116.049.38€	2.116.049.38€	2.116.049.38€	2.116.049.38€	2.116.049.38€
Installation and integration of hardware and software	8.000.00€	10	8.000.00€	8.000.00€	8.000.00€	8.000.00€	8.000.00€	8.000.00€	8.000.00€	8.000.00€	8.000.00€	8.000.00€	8.000.00€
Application Software installation	1.600.00€	10	1.600.00€	1.600.00€	1.600.00€	1.600.00€	1.600.00€	1.600.00€	10.00€	1.600.00€	1.600.00€	1.600.00€	1.600.00€
Operation	21.000.00€	1	0.00€	21.000.00€	42.000.00€	63.000.00€	84.000.00€	105.000.00€	126.000.00€	147.000.00€	168.000.00€	189.000.00€	210.000.00€
Electricity	141.912.00€	1	0.00€	141.912.00€	283.824.00€	425.736.00€	567.648.00€	709.560.00€	851.472.00€	993.384.00€	1.135.296.00€	1.277.208.00€	1.419.120.00€
Space costs	23.148.15€	1	0.00€	23.148.15€	46.296.30€	69.444.44€	92.592.59€	115.740.74€	138.888.89€	162.037.04€	185.185.19€	208.333.33€	231.481.48€
total cost			1.393.149.38€	1.579.209.53€	1.765.269.68€	1.951.329.83€	2.137.389.98€	2.323.450.12€	3.240.420.27€	3.428.070.42€	3.614.130.57€	3.800.190.72€	3.986.250.86€

Simulations, Optimised with Maxeller DFE		Hardware Setup: 1x RECS|Box Deneb Barebone + 3x Microserver Intel E3-1505M v6 + 3x Maxeler DFE											
Other costs		Usage period					Year						
Items	Costs	(years)	Invest	1	2	3	4	5	6	7	8	9	10
Total number of Microservers	3												
Server Hardware	47.731.00€	Some parts 5, some 10	47.731.00€	47.731.00€	47.731.00€	47.731.00€	47.731.00€	47.731.00€	74.368.00 €	74.368.00 €	74.368.00 €	74.368.00 €	74.368.00 €
Installation and integration of hardware and software	2.650.00€	10	2.650.00€	2.650.00€	2.650.00€	2.650.00€	2.650.00€	2.650.00€	2.650.00€	2.650.00€	2.650.00€	2.650.00€	2.650.00€
Application Software installation	250.00€	10	250.00€	250.00€	250.00€	250.00€	250.00€	250.00€	10.00€	250.00€	250.00€	250.00€	250.00€
Operation	2.400.00€	1	0.00€	2.400.00€	4.800.00€	7.200.00€	9.600.00€	12.000.00€	14.400.00€	16.800.00€	19.200.00€	21.600.00€	24.000.00€
Migration (FPGA usage)	5.000.00€	5	5.000.00€	5.000.00€	5.000.00€	5.000.00€	5.000.00€	5.000.00€	6.000.00 €	6.000.00 €	6.000.00 €	6.000.00 €	6.000.00 €
Electricity	165.56€	1	0.00€	165.56€	331.13€	496.69€	662.26€	827.82€	993.38€	1.158.95€	1.324.51€	1.490.08€	1.655.64€
Space costs	750.00€	1	0.00€	750.00€	1.500.00€	2.250.00€	3.000.00€	3.750.00€	4.500.00€	5.250.00€	6.000.00€	6.750.00€	7.500.00€
total cost			55.631.00€	58.946.56€	62.262.13€	65.577.69€	68.893.26€	72.208.82€	102.921.38€	106.476.95€	109.792.51€	113.108.08€	116.423.64€

Figure 6: TCO Table comparing the simulations of biomarker candidates on a standard Microserver (top) and the Maxeler DFE (bottom).

Biomarker subset selection (standard version)		Hardware Setup: 4x RECS|Box Deneb Barebone + 120x Microserver Intel D-1577, 16 Cores, 32 GB RAM											
Other costs		Usage period					Year						
Items	Costs	(years)	Invest	1	2	3	4	5	6	7	8	9	10
Number of Microservers per Chassis	27												
Total number of Chassis	4												
Total number of Microservers	120												
Hardware costs per Chassis	99.340.00€												
Total hardware costs	441.511.11€	Some parts 5, some 10	441.511.11€	441.511.11€	441.511.11€	441.511.11€	441.511.11€	441.511.11€	789.271.11€	789.271.11€	789.271.11€	789.271.11€	789.271.11€
Installation and integration of hardware	8.000.00€	10	8.000.00€	8.000.00€	8.000.00€	8.000.00€	8.000.00€	8.000.00€	8.000.00€	8.000.00€	8.000.00€	8.000.00€	8.000.00€
Application Software installation	1.600.00€	10	1.600.00€	1.600.00€	1.600.00€	1.600.00€	1.600.00€	1.600.00€	10.00€	1.600.00€	1.600.00€	1.600.00€	1.600.00€
Operation	21.000.00€	1	0.00€	21.000.00€	42.000.00€	63.000.00€	84.000.00€	105.000.00€	126.000.00€	147.000.00€	168.000.00€	189.000.00€	210.000.00€
Electricity	9.864.46€	1	0.00€	9.864.46€	19.728.92€	29.593.38€	39.457.84€	49.322.30€	59.186.76€	69.051.23€	78.915.69€	88.780.15€	98.644.61€
Space costs	3.333.33€	1	0.00€	3.333.33€	6.666.67€	10.000.00€	13.333.33€	16.666.67€	20.000.00€	23.333.33€	26.666.67€	30.000.00€	33.333.33€
total cost			451.111.11€	485.308.91€	519.506.70€	553.704.49€	587.902.29€	622.100.08€	1.002.467.88€	1.038.255.67€	1.072.453.46€	1.106.651.26€	1.140.849.05€

Biomarker subset selection (optimized version)		Hardware Setup: 1x RECS|Box Deneb Barebone + 3x Microserver Intel D-1577, 16 Cores, 32 GB RAM											
Other costs		Usage period					Year						
Items	Costs	(years)	Invest	1	2	3	4	5	6	7	8	9	10
Number of Microservers per Chassis	3												
Total number of Chassis	1												
Total number of Microservers	3												
Hardware costs per Chassis	29.788.00€												
Total hardware costs	29.788.00€	Some parts 5, some 10	29.788.00€	29.788.00€	29.788.00€	29.788.00€	29.788.00€	29.788.00€	38.482.00€	38.482.00€	38.482.00€	38.482.00€	38.482.00€
Installation and integration of hardware	500.00€	10	500.00€	500.00€	500.00€	500.00€	500.00€	500.00€	500.00€	500.00€	500.00€	500.00€	500.00€
Application Software installation	200.00€	10	200.00€	200.00€	200.00€	200.00€	200.00€	200.00€	10.00€	200.00€	200.00€	200.00€	200.00€
Operation	4.500.00€	1	0.00€	4.500.00€	9.000.00€	13.500.00€	18.000.00€	22.500.00€	27.000.00€	31.500.00€	36.000.00€	40.500.00€	45.000.00€
Electricity	246.61€	1	0.00€	246.61€	493.22€	739.83€	986.45€	1.233.06€	1.479.67€	1.726.28€	1.972.89€	2.219.50€	2.466.12€
Space costs	750.00€	1	0.00€	750.00€	1.500.00€	2.250.00€	3.000.00€	3.750.00€	4.500.00€	5.250.00€	6.000.00€	6.750.00€	7.500.00€
total cost			30.488.00€	35.984.61€	41.481.22€	46.977.83€	52.474.45€	57.971.06€	71.971.67€	77.658.28€	83.154.89€	88.651.50€	94.148.12€

Figure 7: TCO Table comparing the subset selection of biomarker candidates achieving the same total performance as the optimised version by an increased amount of hardware.

Classifier (Python baseline version)		Hardware Setup: 60x RECS|Box Deneb Barebone + 1632x Microserver Intel E-2176M, 6 Cores, 32 GB RAM											
Other costs		Usage period					Year						
Items	Costs	(years)	Invest	1	2	3	4	5	6	7	8	9	10
Number of Microservers per Chassis	27												
Total number of Chassis	60												
Total number of Microservers	1632												
Hardware costs per Chassis	45.907.00€												
Total hardware costs	2.774.823.11€	Some parts 5, some 10	2.774.823.11€	2.774.823.11€	2.774.823.11€	2.774.823.11€	2.774.823.11€	2.774.823.11€	4.274.631.11€	4.274.631.11€	4.274.631.11€	4.274.631.11€	4.274.631.11€
Installation and integration of hardware	8.000.00€	10	8.000.00€	8.000.00€	8.000.00€	8.000.00€	8.000.00€	8.000.00€	8.000.00€	8.000.00€	8.000.00€	8.000.00€	8.000.00€
Application Software installation	1.600.00€	10	1.600.00€	1.600.00€	1.600.00€	1.600.00€	1.600.00€	1.600.00€	10.00€	1.600.00€	1.600.00€	1.600.00€	1.600.00€
Operation	21.000.00€	1	0.00€	21.000.00€	42.000.00€	63.000.00€	84.000.00€	105.000.00€	126.000.00€	147.000.00€	168.000.00€	189.000.00€	210.000.00€
Electricity	193.000.32€	1	0.00€	193.000.32€	386.000.64€	579.000.96€	772.001.28€	965.001.60€	1.158.001.92€	1.351.002.24€	1.544.002.56€	1.737.002.88€	1.930.003.20€
Space costs	45.333.33€	1	0.00€	45.333.33€	90.666.67€	136.000.00€	181.333.33€	226.666.67€	272.000.00€	317.333.33€	362.666.67€	408.000.00€	453.333.33€
total cost			2.784.423.11€	3.043.756.76€	3.303.090.42€	3.562.424.07€	3.821.757.72€	4.081.091.38€	5.838.643.03€	6.099.566.68€	6.358.900.34€	6.618.233.99€	6.877.567.64€

Classifier (Optimized XiTAO Version)		Hardware Setup: 1x RECS|Box Deneb Barebone + 3x Microserver Intel E-2176M, 6 Cores, 32 GB RAM											
Other costs		Usage period					Year						
Items	Costs	(years)	Invest	1	2	3	4	5	6	7	8	9	10
Number of Microservers per Chassis	3												
Total number of Chassis	1												
Total number of Microservers	3												
Hardware costs per Chassis	23.851.00€												
Total hardware costs	23.851.00€	Some parts 5, some 10	23.851.00€	23.851.00€	23.851.00€	23.851.00€	23.851.00€	23.851.00€	26.608.00€	26.608.00€	26.608.00€	26.608.00€	26.608.00€
Installation and integration of hardware	500.00€	10	500.00€	500.00€	500.00€	500.00€	500.00€	500.00€	500.00€	500.00€	500.00€	500.00€	500.00€
Application Software installation	250.00€	10	250.00€	250.00€	250.00€	250.00€	250.00€	250.00€	10.00€	250.00€	250.00€	250.00€	250.00€
Operation	4.500.00€	1	0.00€	4.500.00€	9.000.00€	13.500.00€	18.000.00€	22.500.00€	27.000.00€	31.500.00€	36.000.00€	40.500.00€	45.000.00€
Electricity	469.10€	1	0.00€	469.10€	938.20€	1.407.29€	1.876.39€	2.345.49€	2.814.59€	3.283.69€	3.752.78€	4.221.88€	4.690.98€
Space costs	750.00€	1	0.00€	750.00€	1.500.00€	2.250.00€	3.000.00€	3.750.00€	4.500.00€	5.250.00€	6.000.00€	6.750.00€	7.500.00€
total cost			24.601.00€	30.320.10€	36.039.20€	41.758.29€	47.477.39€	53.196.49€	61.432.59€	67.391.69€	73.110.78€	78.829.88€	84.548.98€

Figure 8: TCO Table comparing the calculation of classifier performances achieving the same total performance as the optimised version by an increased amount of hardware.

7. Machine Learning Use case

The TCO charts presented consider two scenarios:

1. Edge application where an YOLOv3 on an Nvidia Xavier can be optimised to get better performance (FPS) even when ported to the much cheaper platform Nvidia Jetson TX2, while preserving the power consumption (W)
2. Cloud application of replacing an Nvidia GeForce 2060 RTX with an Nvidia TX2

For the embedded use case, the optimised version (on Nvidia TX2) shows 1.75x better energy efficiency than the unoptimised model (on Nvidia Xavier), while saving 234 € in hardware cost, resulting in 36.8% savings in hardware cost. For the cloud application, the energy efficiency increases by 28x and the power consumption decreases by 20x. The optimised cloud system is expected to break even, in terms of costs, after 2 to 3 years of service and save 1814 € after 10 years.

The Machine Learning use case is both relevant in an edge environment as well as in a data centre, as shown. Therefore two different TCO calculations have been used for these two different contexts.

7.1. Optimisation on the Edge

In Figures 9 and 10, we consider the scenario where the detection model YOLOv3 is running at maximum (measured) throughput on the Nvidia Xavier machine, with an estimated cost of 636 €. On this device, the measured throughput is 11 FPS with a power consumption of 6.21 W.

After applying EmbeDL to optimise the YOLOv3 model, the model requires much less compute power. We present the case where the optimised model is ported to the much Nvidia Jetson TX2 machine (estimated cost of 402 €). As presented in the charts, the power consumption is almost identical while greatly increasing the performance of the model. The FPS is almost doubled (19.2 FPS) while saving 234 € (36.8%) in hardware costs.

7.2. Optimisation on the Cloud

In the case of cloud computing we focus on the Nvidia Geforce RTX 2060 GPU (maximum 160W and assumed cost 359 €) on which the YOLOv3 model operates in Figures 11 and 12. No actual experiments were performed on this device, but the performance is assumed by linear interpolation from the Nvidia Xavier FLOPS, which gives us an estimated value of 14 FPS. Also, the hardware utilisation is assumed to be 80%, which leads to a power consumption of 128W.

The optimised model is then ported to the Nvidia Jetson TX2 as in the Edge case. By porting to this hardware, the energy efficiency increases by 28x and the power consumption decreases by 20x. In terms of costs, the Jetson platform is 43 € more expensive than the RTX 2060 but the costs savings from the decreased power consumption greatly outweigh this hardware cost as well as the costs for porting. The optimised system is expected to break even, in terms of costs, after 2 to 3 years of service and save 1814 € after 10 years.

7.3. TCO calculations

The edge case optimisation focuses on the maximisation of the performance (FPS or Latency). This can prove critical in the case of an automotive application, where a slower system could be the deciding factor in a dangerous situation. We still show that in this case, costs can be saved by changing hardware. One could argue that the system could potentially save energy by slowing down the model to a certain latency specification, but this case was not considered. On the other hand, applications running on the cloud typically don't focus on latency as safety-critical autonomous vehicles. In the case of cloud, we focus on decreasing the power consumption as much as possible in order to save costs over time. Overall TCO savings are 29.3% for the edge case and 43.8% for the cloud case.

LEGaTO Use Case Machine Learning, Nvidia Xavier, Unoptimised YoloV3 Model														
Total cost of ownership (TCO) is an analysis that places a single value on the complete lifecycle of a capital purchase.														
Hardware costs			costs/unit	overall costs										Nvidia Xavier
Server unit RAM	32	GB RAM												
Server unit CPU cores	8	CPU cores												
Number of server units	1	nodes	636,00€	636,00€										
Number of GPUs	1	GPUs	0,00€	0,00€										
Number of FPGAs	0	FPGAs	0,00€	0,00€										
Total number of chassis	1	Chassis												
Overall space occupation	n/a	RU												
Overall hardware cost				**636,00€**										
Performance / node	11,00													
power consumption [W]	6,21													
Total space in U	0,00													
Energy efficiency		metrics												
Performance of above hardware	11,00	Perf / Sec												
Energy efficiency	1,77	Perf / Joule												
Electricity costs		day	month	year										
PuE (constant)	1,5													
Average server power consumption (W)	6,2	0,2	6,7	81,7										
electricity cost 1kWh (EUR)	0,15	0	1	**12**	Yearly electricity costs									
Other costs		Usage period							Year					
Items	Costs	(years)	Invest	1	2	3	4	5	6	7	8	9	10	
Server Hardware	636,00€	5	636,00€	636,00€	636,00€	636,00€	636,00€	636,00€	1.272,00€	1.272,00€	1.272,00€	1.272,00€	1.272,00€	
Installation and integration of hardware and software up to OS	100,00€	5	100,00€	100,00€	100,00€	100,00€	100,00€	100,00€	200,00€	200,00€	200,00€	200,00€	200,00€	
Application software installation	0,00€	5	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	
Network (hardware and software)	0,00€	n/a	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	
Operation	0,00€	1	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	
Migration	0,00€	n/a	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	
Electricity	12,25€	1	0,00€	12,25€	24,50€	36,75€	49,00€	61,25€	73,49€	85,74€	97,99€	110,24€	122,49€	
Space costs	0,00€	n/a	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	
Upgrade	0,00€	n/a	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	
total cost			**736,00€**	**748,25€**	**760,50€**	**772,75€**	**785,00€**	**797,25€**	**1.545,49€**	**1.557,74€**	**1.569,99€**	**1.582,24€**	**1.594,49€**	

Figure 9: TCO Table for the non-optimised Machine Learning use case on Nvidia Xavier (Edge)

LEGaTO Use Case Machine Learning, Nvidia TX2, Optimised YoloV3 Model														
Total cost of ownership (TCO) is an analysis that places a single value on the complete lifecycle of a capital purchase.														
Hardware costs			costs/unit	overall costs										Nvidia TX2
Server unit RAM	8	GB RAM												
Server unit CPU cores	6	CPU cores												
Number of server units	1	nodes	402,00€	402,00€										
Number of GPUs	1	GPUs	0,00€	0,00€										
Number of FPGAs	0	FPGAs	0,00€	0,00€										
Total number of chassis	1	Chassis												
Overall space occupation	n/a	RU												
Overall hardware cost				**402,00€**										
Performance / node	19,20													
power consumption [W]	6,22													
Total space in U	0,00													
Energy efficiency		metrics												
Performance of above hardware	19,20	Perf / Sec												
Energy efficiency	3,09	Perf / Joule												
Electricity costs		day	month	year										
PuE (constant)	1,5													
Average server power consumption (W)	6,2	0,2	6,7	81,8										
electricity cost 1kWh (EUR)	0,15	0	1	**12**	Yearly electricity costs									
Other costs		Usage period							Year					
Items	Costs	(years)	Invest	1	2	3	4	5	6	7	8	9	10	
Server Hardware	402,00€	5	402,00€	402,00€	402,00€	402,00€	402,00€	402,00€	804,00€	804,00€	804,00€	804,00€	804,00€	
Installation and integration of hardware and software up to OS	100,00€	5	100,00€	100,00€	100,00€	100,00€	100,00€	100,00€	200,00€	200,00€	200,00€	200,00€	200,00€	
Application software installation	0,00€	5	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	
Network (hardware and software)	0,00€	n/a	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	
Operation	0,00€	1	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	
Migration	0,00€	n/a	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	
Electricity	12,27€	1	0,00€	12,27€	24,53€	36,80€	49,07€	61,33€	73,60€	85,87€	98,13€	110,40€	122,67€	
Space costs	0,00€	n/a	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	
Upgrade	0,00€	n/a	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	
total cost			**502,00€**	**514,27€**	**526,53€**	**538,80€**	**551,07€**	**563,33€**	**1.077,60€**	**1.089,87€**	**1.102,13€**	**1.114,40€**	**1.126,67€**	

Figure 10: TCO Table for the optimised Machine Learning use case on Nvidia TX2 (Edge)

LEGaTO Use Case Machine Learning, Nvidia GeForce RTX 2060, Unoptimised YoloV3 Model														
Total cost of ownership (TCO) is an analysis that places a single value on the complete lifecycle of a capital purchase.														
Hardware costs			costs/unit	overall costs										
Server unit RAM	32	GB RAM												
Server unit CPU cores	8	CPU cores												
Number of server units	1	nodes	359,00€	359,00€										
Number of GPUs	1	GPUs	0,00€	0,00€										
Number of FPGAs	0	FPGAs	0,00€	0,00€										
Total number of chassis	1	Chassis												
Overall space occupation	n/a	RU												
Overall hardware cost				**359,00€**										
Performance / node	14,09													
power consumption [W]	128,00													
Total space in U	0,00													
Energy efficiency		metrics												
Performance of above hardware	14,09	Perf / Sec												
Energy efficiency	0,11	Perf / Joule												
Electricity costs		day	month	year										
PuE (constant)	1,5													
Average server power consumption (W)	128,0	4,6	138,2	1681,9										
electricity cost 1kWh (EUR)	0,15	1	21	**252**	Yearly electricity costs									
Other costs		Usage period			Year									
Items	Costs	(years)	Invest	1	2	3	4	5	6	7	8	9	10	
Server Hardware	359,00€	5	359,00€	359,00€	359,00€	359,00€	359,00€	359,00€	718,00€	718,00€	718,00€	718,00€	718,00€	
software up to OS	100,00€	5	100,00€	100,00€	100,00€	100,00€	100,00€	100,00€	200,00€	200,00€	200,00€	200,00€	200,00€	
Application software installation	0,00€	5	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	
Network (hardware and software)	100,00€	5	100,00€	100,00€	100,00€	100,00€	100,00€	100,00€	200,00€	10,00€	200,00€	200,00€	200,00€	
Operation	50,00€	1	0,00€	50,00€	100,00€	150,00€	200,00€	250,00€	300,00€	350,00€	400,00€	450,00€	500,00€	
Migration	0,00€	n/a	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	
Electricity	252,29€	1	0,00€	252,29€	504,58€	756,86€	1.009,15€	1.261,44€	1.513,73€	1.766,02€	2.018,30€	2.270,59€	2.522,88€	
Space costs	0,00€	n/a	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	
Upgrade	0,00€	n/a	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	
total cost			**559,00€**	**861,29€**	**1.163,58€**	**1.465,86€**	**1.768,15€**	**2.070,44€**	**2.931,73€**	**3.044,02€**	**3.536,30€**	**3.838,59€**	**4.140,88€**	

Figure 11: TCO Table for the non-optimised Machine Learning use case on Nvidia Xavier (Cloud)

LEGaTO Use Case Machine Learning, Nvidia Jetson TX2, Optimised YoloV3 Model														
Total cost of ownership (TCO) is an analysis that places a single value on the complete lifecycle of a capital purchase.														
Hardware costs			costs/unit	overall costs										
Server unit RAM	8	GB RAM												
Server unit CPU cores	6	CPU cores												
Number of server units	1	nodes	402,00€	402,00€										
Number of GPUs	1	GPUs	0,00€	0,00€										
Number of FPGAs	0	FPGAs	0,00€	0,00€										
Total number of chassis	1	Chassis												
Overall space occupation	n/a	RU												
Overall hardware cost				**402,00€**										
Performance / node	19,20													
power consumption [W]	6,22													
Total space in U	0,00													
Energy efficiency		metrics												
Performance of above hardware	19,20	Perf / Sec												
Energy efficiency	3,09	Perf / Joule												
Electricity costs		day	month	year										
PuE (constant)	1,5													
Average server power consumption (W)	6,2	0,2	6,7	81,8										
electricity cost 1kWh (EUR)	0,15	0	1	**12**	Yearly electricity costs									
Other costs		Usage period			Year									
Items	Costs	(years)	Invest	1	2	3	4	5	6	7	8	9	10	
Server Hardware	402,00€	5	402,00€	402,00€	402,00€	402,00€	402,00€	402,00€	804,00€	804,00€	804,00€	804,00€	804,00€	
Installation and integration of hardware and software up to OS	100,00€	5	100,00€	100,00€	100,00€	100,00€	100,00€	100,00€	200,00€	200,00€	200,00€	200,00€	200,00€	
Application software installation	0,00€	5	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	
Network (hardware and software)	100,00€	5	100,00€	100,00€	100,00€	100,00€	100,00€	100,00€	200,00€	10,00€	200,00€	200,00€	200,00€	
Operation	50,00€	1	0,00€	50,00€	100,00€	150,00€	200,00€	250,00€	300,00€	350,00€	400,00€	450,00€	500,00€	
Migration	500,00€	n/a	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	
Electricity	12,27€	1	0,00€	12,27€	24,53€	36,80€	49,07€	61,33€	73,60€	85,87€	98,13€	110,40€	122,67€	
Space costs	0,00€	n/a	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	
Upgrade	0,00€	n/a	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	
total cost			**1.102,00€**	**1.164,27€**	**1.226,53€**	**1.288,80€**	**1.351,07€**	**1.413,33€**	**2.077,60€**	**1.949,87€**	**2.202,13€**	**2.264,40€**	**2.326,67€**	

Figure 12: TCO Table for the optimised Machine Learning use case on Nvidia TX2 (Cloud)

8. Secure IoT Gateway use case

The Secure IoT Gateway is not comparable to other use cases as it doesn't leverage the LEGaTO hardware or any other software than the Network Cockpit. The main goal and benefit of this use case is to add extra security to the other use cases, as described in D5.3 chapter 7 using COTS embedded hardware, which is already available and tested.

This TCO analysis addresses costs for a manual three-site VPN scenario in contrast to the Secure IoT Gateway solution. Both scenarios are based on the same hardware, thus initial costs for devices (4.052,44 €) and energy costs (300 € per year) stay the same for both scenarios. A comparison between an unsecured network without any protection for IoT devices was not made, because there are no additional costs in such a setup. This TCO analysis is independent of the IoT devices and existing network infrastructure. The main financial differences can be found in the manual installation and maintenance costs. The Secure IoT Gateway provides an easy and time-efficient way of handling the VPN connections, therefore lowering the initial installation costs as well as the regular maintenance costs. Using the Network Cockpit to install and configure the Local Gateway and the IoT Bridges, the installation takes about 8 hours. The necessary maintenance effort over the years is significantly reduced as updates or configuration changes can be applied very fast and without being able to access the local network. When not using the Network Cockpit, it would take about 300 hours to set up the structure. Overall this results in a 40% reduced TCO for 10 years compared to the manual installation.

Additionally, the increase in security and the smaller risk to have a successful attack against the IoT devices was not considered as it's hard to estimate costs for these scenarios. The financial loss in such a case depends on many parameters and thus was not calculated. With even bigger installations, the TCO advantage would further increase.

LEGaTO Use Case Secure IoT Gateway						
Total cost of ownership (TCO) is an analysis that places a single value on the complete lifecycle of a capital purchase.						
This describes the costs with the new Network Cockpit that handles the installation and updates of the IoT-Bridges and Gateways compared to a manual setup done by a technican. The hardware is the same in both cases. The Local and Cluster Gateways are a 1U shortrack chassis with an Intel Atom and OPNsense installed on it. The IoT Bridges are cigarette-box sized minicomputers with different ARM processors and OpenWRT installed.						
Hardware costs			costs/unit	overall costs	typical power	total power
Number of Cluster Gateways	1	nodes	745,61€	745,61€	17,2	17,2
Number of Local Gateways	10	nodes	745,61€	7.456,10€	17,2	172
Number of IoT Bridge 10	150	nodes	29,00€	4.350,00€	1,2	180
Number of IoT Bridge 50	100	nodes	39,00€	3.900,00€	1,7	170
Number of IoT Bridge 100	50	nodes	49,00€	2.450,00€	2,1	105
Total number of chassis	311	nodes				
Overall hardware cost				**18.901,71€**		
power consumption [W]	644,20					
Total space in U	1,00					
Electricity costs		day	month	year		
PuE (constant)	1,2					
Average server power consumption (W)	644,2	18,6	556,6	6771,8		
electricity cost 1kWh (EUR)	0,25	5	139	**1693**	Yearly electricity costs	
Other costs		Usage period		**Year**		**cost**
Items	Costs	(years)	Invest	1	10	**difference**
Server Hardware	18.901,71€	10	18.901,71€	18.901,71€	18.901,71€	
Network (hardware and software)	51,30€	10	51,30€	51,30€	51,30€	
Electricity	1.692,96€	1	0,00€	1.692,96€	16.929,58€	
Space costs	250,00€	1	0,00€	250,00€	2.500,00€	
total independent cost			**18.953,01€**	**20.895,97€**	**38.382,59€**	
Manual installation and integration of hardware and software	22.500,00€	10	22.500,00€	22.500,00€	22.500,00€	
Manual Operation	945,09€	1	0,00€	945,09€	9.450,86€	
total cost with manual installation			**41.453,01 €**	**44.341,05 €**	**70.333,44 €**	100%
Installation and integration of hardware and software with network cockpit	1.950,00€	10	1.950,00€	1.950,00€	1.950,00€	
Operation with network cockpit	189,02€	1	0,00€	189,02€	1.890,17€	
total cost with network cockpit			**20.903,01 €**	**23.034,98 €**	**42.222,76 €**	60,03%

Figure 9: TCO Table for a typical Secure IoT Gateway installation

The table above shows a typical installation how it could be done in a company with 10 branches and over 300 IoT Gateways. These could be mounted to machines that have numerous different IoT sensors mounted on them to track how the machine is behaving. In the following table a much smaller installation with only 3 branches and 30 IoT Gateways is displayed. Even in that small installation scenario the TCO advantage is still 24,6% compared to an manual setup of the devices.

LEGaTO Use Case Secure IoT Gateway						
Total cost of ownership (TCO) is an analysis that places a single value on the complete lifecycle of a capital purchase.						
This describes the costs with the new Network Cockpit that handles the installation and updates of the IoT-Bridges and Gateways compared to a manual setup done by a technican. The hardware is the same in both cases. The Local and Cluster Gateways are a 1U shortrack chassis with an Intel Atom and OPNsense installed on it. The IoT Bridges are cigarette-box sized minicomputers with different ARM processors and OpenWRT installed.						
Hardware costs			costs/unit	overall costs	typical power	total power
Number of Cluster Gateways	1	nodes	745,61€	745,61€	17,2	17,2
Number of Local Gateways	3	nodes	745,61€	2.236,83€	17,2	51,6
Number of IoT Bridge 10	15	nodes	29,00€	435,00€	1,2	18
Number of IoT Bridge 50	10	nodes	39,00€	390,00€	1,7	17
Number of IoT Bridge 100	5	nodes	49,00€	245,00€	2,1	10,5
Total number of chassis	34	nodes				
Overall hardware cost				**4.052,44€**		
power consumption [W]	114,30					
Total space in U	1,00					
Electricity costs		day	month	year		
PuE (constant)	1,2					
Average server power consumption (W)	114,3	3,3	98,8	1201,5		
electricity cost 1kWh (EUR)	0,25	1	25	**300**	Yearly electricity costs	
Other costs		Usage period		**Year**		**cost**
Items	Costs	(years)	Invest	1	10	**difference**
Server Hardware	4.052,44€	10	4.052,44€	4.052,44€	4.052,44€	
Network (hardware and software)	51,30€	10	51,30€	51,30€	51,30€	
Electricity	300,38€	1	0,00€	300,38€	3.003,80€	
Space costs	250,00€	1	0,00€	250,00€	2.500,00€	
total independent cost			**4.103,74€**	**4.654,12€**	**9.607,54€**	
Manual installation and integration of hardware and software	2.250,00€	10	2.250,00€	2.250,00€	2.250,00€	
Manual Operation	202,62€	1	0,00€	202,62€	2.026,22€	
total cost with manual installation			**6.353,74 €**	**7.106,74 €**	**13.883,76 €**	100%
Installation and integration of hardware and software with network cockpit	600,00€	10	600,00€	600,00€	600,00€	
Operation with network cockpit	40,52€	1	0,00€	40,52€	405,24€	
total cost with network cockpit			**4.703,74 €**	**5.294,64 €**	**10.612,79 €**	76,44%

Figure 10: TCO Table for an alternative small Secure IoT Gateway installation

9. Conclusion

In this deliverable, we have evaluated and compared the Total Cost of Ownership (TCO) savings as well as performance and energy-efficiency gains achieved by the use of LEGaTO technology. We compared the TCO of the baseline hardware, and unoptimised LEGaTO use cases with the LEGaTO hardware and optimised LEGaTO use cases.

The savings achieved depend on the platform that is used as well as the software optimisations performed. The estimates show that the use of LEGaTO stack can bring the following significant savings to TCO for each use case (TCO after ten years, when considering infrastructure upgrade): for the Smart Home use case 81.6%, for the Smart City use case 70%, for Infection Research use case from 91.8% to 98.8%, for Machine Learning use case 43.8% and for Secure IoT Gateway use case 40%.

10. References

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11. Annex A: Additional TCO experiments

11.1. A.1 Smart City Use case

LEGaTO Use Case Smart City, LEGaTO-Hardware, Optimised Software														
Total cost of ownership (TCO) is an analysis that places a single value on the complete lifecycle of a capital purchase.														
Hardware costs			Costs / unit	Overall costs										
Microserver RAM	16	GB RAM												
Microserver CPU cores	8	CPU cores												
Number of Microservers	1	nodes	1.100,00€	1.100,00€										
Number of GPUs	1	GPUs	0,00€	0,00€										
Number of FPGAs	0	FPGAs	0,00€	0,00€										
Total number of M2DC Server Barebones	0	Barebones	0,00€	0,00€										
Overall space occupation	0	RU												
Overall hardware cost				**1.100,00€**										
Performance / node	8,52E+09	FLOPS												
power consumption [W]	26,46													
Total space in U	1,00													
Energy efficiency		metrics												
Performance of above hardware	8,52E+09	Perf / Sec												
Energy efficiency	3,22E+08	Perf / Joule	**gain:**	459,68%										
Electricity costs		**day**	**month**	**year**										
PUE (constant)	1													
Average server power consumption (W)	26,5	0,6	19	232										
electricity cost 1kWh (EUR)	0,1	0,06€	1,90€	**23,18€**	Yearly electricity costs									

		Usage period		Year									
Other costs	Costs	(years)	Invest	1	2	3	4	5	6	7	8	9	10
Server Hardware	1.100,00€	10	1.100,00€	1.100,00€	1.100,00€	1.100,00€	1.100,00€	1.100,00€	1.100,00€	1.100,00€	1.100,00€	1.100,00€	1.100,00€
Installation and integration of hardware and software up to OS	1.000,00€	3	1.000,00€	1.000,00€	1.000,00€	1.000,00€	2.000,00€	2.000,00€	2.000,00€	3.000,00€	3.000,00€	3.000,00€	4.000,00€
Application software installation	500,00€	3	500,00€	500,00€	500,00€	500,00€	1.000,00€	1.000,00€	1.000,00€	1.500,00€	1.500,00€	1.500,00€	2.000,00€
Network (hardware and software)	500,00€	10	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€
Operation	55,00€	1	0,00€	55,00€	110,00€	165,00€	220,00€	275,00€	330,00€	385,00€	440,00€	495,00€	550,00€
Migration	0,00€	10	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€
Electricity	23,18€	1	0,00€	23,18€	46,35€	69,53€	92,71€	115,88€	139,06€	162,24€	185,41€	208,59€	231,77€
Space costs	0,00€	1	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€
Upgrade	1.900,00€	3	0,00€	0,00€	0,00€	0,00€	1.900,00€	1.900,00€	1.900,00€	3.800,00€	3.800,00€	3.800,00€	5.700,00€
Total Cost			**3.100,00€**	**3.178,18€**	**3.256,35€**	**3.334,53€**	**6.812,71€**	**6.890,88€**	**6.969,06€**	**10.447,24€**	**10.525,41€**	**10.603,59€**	**14.081,77€**

Figure 14: TCO Table for a prototype consisting of one Nvidia Xavier board running the Smart City Use case at normal power mode 0.

LEGaTO Use Case Smart City, LEGaTO-Hardware, Optimised Software														
Total cost of ownership (TCO) is an analysis that places a single value on the complete lifecycle of a capital purchase.														
Hardware costs			Costs / unit	Overall costs										
Microserver RAM	16	GB RAM												
Microserver CPU cores	8	CPU cores												
Number of Microservers	1	nodes	1.100,00€	1.100,00€										
Number of GPUs	1	GPUs	0,00€	0,00€										
Number of FPGAs	0	FPGAs	0,00€	0,00€										
Total number of M2DC Server Barebones	0	Barebones	0,00€	0,00€										
Overall space occupation	0	RU												
Overall hardware cost				**1.100,00€**										
Performance / node	4,79E+09	FLOPS												
power consumption [W]	10,37													
Total space in U	1,50													
Energy efficiency		metrics												
Performance of above hardware	4,79E+09	Perf / Sec												
Energy efficiency	4,61E+08	Perf / Joule	**gain:**	702,09 %										
Electricity costs		**day**	**month**	**year**										
PUE (constant)	1													
Average server power consumption (W)	10,4	0,2	7	91										
electricity cost 1kWh (EUR)	0,1	0,02€	0,75€	**9,09€**	Yearly electricity costs									

		Usage period		Year									
Other costs	Costs	(years)	Invest	1	2	3	4	5	6	7	8	9	10
Server Hardware	1.100,00€	10	1.100,00€	1.100,00€	1.100,00€	1.100,00€	1.100,00€	1.100,00€	1.100,00€	1.100,00€	1.100,00€	1.100,00€	1.100,00€
Installation and integration of hardware and software up to OS	1.000,00€	3	1.000,00€	1.000,00€	1.000,00€	1.000,00€	2.000,00€	2.000,00€	2.000,00€	3.000,00€	3.000,00€	3.000,00€	4.000,00€
Application software installation	500,00€	3	500,00€	500,00€	500,00€	500,00€	1.000,00€	1.000,00€	1.000,00€	1.500,00€	1.500,00€	1.500,00€	2.000,00€
Network (hardware and software)	500,00€	10	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€
Operation	55,00€	1	0,00€	55,00€	110,00€	165,00€	220,00€	275,00€	330,00€	385,00€	440,00€	495,00€	550,00€
Migration	0,00€	10	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€
Electricity	9,09€	1	0,00€	9,09€	18,18€	27,26€	36,35€	45,44€	54,53€	63,61€	72,70€	81,79€	90,88€
Space costs	0,00€	1	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€
Upgrade	1.900,00€	3	0,00€	0,00€	0,00€	0,00€	1.900,00€	1.900,00€	1.900,00€	3.800,00€	3.800,00€	3.800,00€	5.700,00€
Total Cost			**3.100,00€**	**3.164,09€**	**3.228,18€**	**3.292,26€**	**6.756,35€**	**6.820,44€**	**6.884,53€**	**10.348,61€**	**10.412,70€**	**10.476,79€**	**13.940,88€**

Figure 15: TCO Table for a prototype consisting of one Nvidia Xavier board running the Smart City Use case at low-power mode 3.

LEGaTO Use Case Smart City, LEGaTO-Hardware, Optimised Software														
Total cost of ownership (TCO) is an analysis that places a single value on the complete lifecycle of a capital purchase.														
Hardware costs			Costs / unit	Overall costs										
Microserver RAM	16	GB RAM												
Microserver CPU cores	8	CPU cores												
Number of Microservers	2	nodes	1.100,00€	2.200,00€										
Number of GPUs	2	GPUs	0,00€	0,00€										
Number of FPGAs	0	FPGAs	0,00€	0,00€										
Total number of M2DC Server Barebones	0	Barebones	0,00€	0,00€										
Overall space occupation	0	RU												
Overall hardware cost				**2.200,00€**										
Performance / node	5,99E+09	FLOPS												
power consumption [W]	25,05													
Total space in U	2,00													
Energy efficiency		metrics												
Performance of above hardware	1,20E+10	Perf / Sec												
Energy efficiency	2,39E+08	Perf / Joule	**gain:**	315,56 %										
Electricity costs		**day**	**month**	**year**										
PUE (constant)	1													
Average server power consumption (W)	50,1	1,2	36	439										
electricity cost 1kWh (EUR)	0,1	0,12€	3,61€	**43,88€**	Yearly electricity costs									
		Usage period			Year									
Other costs	Costs	(years)	Invest	1	2	3	4	5	6	7	8	9	10	
Server Hardware	2.200,00€	10	2.200,00€	2.200,00€	2.200,00€	2.200,00€	2.200,00€	2.200,00€	2.200,00€	2.200,00€	2.200,00€	2.200,00€	2.200,00€	
Installation and integration of hardware and software up to OS	1.000,00€	3	1.000,00€	1.000,00€	1.000,00€	1.000,00€	2.000,00€	2.000,00€	2.000,00€	3.000,00€	3.000,00€	3.000,00€	4.000,00€	
Application software installation	500,00€	3	500,00€	500,00€	500,00€	500,00€	1.000,00€	1.000,00€	1.000,00€	1.500,00€	1.500,00€	1.500,00€	2.000,00€	
Network (hardware and software)	500,00€	10	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	500,00€	
Operation	110,00€	1	0,00€	110,00€	220,00€	330,00€	440,00€	550,00€	660,00€	770,00€	880,00€	990,00€	1.100,00€	
Migration	0,00€	10	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	
Electricity	43,88€	1	0,00€	43,88€	87,77€	131,65€	175,54€	219,42€	263,31€	307,19€	351,08€	394,96€	438,85€	
Space costs	0,00€	1	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	0,00€	
Upgrade	3.000,00€	3	0,00€	0,00€	0,00€	0,00€	3.000,00€	3.000,00€	3.000,00€	6.000,00€	6.000,00€	6.000,00€	9.000,00€	
Total Cost			**4.200,00€**	**4.353,88€**	**4.507,77€**	**4.661,65€**	**9.315,54€**	**9.469,42€**	**9.623,31€**	**14.277,19€**	**14.431,08€**	**14.584,96€**	**19.238,85€**	

Edge Server Hardware:
t.recs edge Server
2x Nvidia AGX Xavier

Figure 16: TCO Table for a prototype consisting of two Nvidia Xavier boards running the Smart City Use case at normal power mode 0.