COTS or Custom Made?

A Multi-Criteria Decision Analysis for Industrial Control Systems

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***Abstract*—The choice between *custom made* electronics and the use of *commercial of the shelf* (COTS) components is often not trivial for industrial control systems. The selection is particularly challenging, when required quantities or specific requirements do not give a clear sign for the one or the other approach. While a consideration of the resulting costs (development costs and product costs) gives some indication, only a broader view helps to perform a sound decision. In this work, a set of decision criteria (targets to be reached by the control unit) and a decision method based on *multi-criteria decision analysis* are presented for industrial control systems. The presented approach is considering COTS devices, custom made devices as well as a combination of both. Moreover, a case study with three industrial control systems is presented showing the application of the approach.**

Keywords–commercial of the shelf; electronic design decisions; industrial control units; MCDA

I. Introduction

This article is extending previous work on design decisions for industrial control units presented at CENICS 2015 [1]. The most important extensions are the inclusion of further decision criteria, iterations in the specification phase, as well as a proposal for the selection procedure itself.

Commercial of the shelf (COTS) components as programmable logic controllers (PLCs) and industrial PCs (IPCs) are widely used as control units in industrial automation (For this article, we follow the following definition for COTS: A COTS device can be bought from a catalog without modifications [2]). In some applications, companies are faced with the decision if a *custom made* (CM) design of a control unit might be beneficial for their products and systems. Such a CM design includes the development of the control electronics, the corresponding software as well as mechanical parts as the housing and the user interface. In other applications, a change from a custom made design of control units to COTS components is discussed (mostly with the idea of cost reduction in mind).

Both approaches have their specific advantages and disadvantages. A custom made device often comes with an optimized functionality and an attractive price of the final product, but involves much more effort than the required development activities. Especially in case of safety or mission critical systems, it has to be assured that specific requirements (temperature range, failure rate, electrical robustness, etc.) are met over the complete product life cycle (and not only with a prototype during development). While a custom made design allows full control of the final product, all relevant aspects have to be verified. These activities are performed on basis of prototypes and first series devices, but also have to be reconsidered in case of all changes (e.g., if obsolete memory chips require replacement, at least an impact analysis is required but often several verification, validation and certification activities have to be redone).

On the other hand, the use of COTS devices often requires more than applying a plug and play procedure. Depending on the application, the selection of a suitable device could be challenging. And also systems based on COTS devices have to undergo verification, validation and certification activities. Moreover, it could be required to establish specific relationships with the suppliers and/or to perform additional tests on the COTS components if they are applied in critical applications (examples can be found in [2]).

In both cases, the complete life cycle of the product has to be considered for a sound selection. An approach for such a selection is the so called Total Cost of Ownership (TCO) [3] that aims to consider all cost factors of a product during product life. To supplement existing approaches with the required technical data, this article deals with the differences of the following approaches for industrial control units:

1) COTS - *commercial of the shelf*
2) CM - *custom made*
3) Combination of 1 and 2.

The main focus of this article is on electronic control units (including their software), but not on pure software products as discussed for example in [4].

As a basis for a systematic selection procedure, we collect relevant selection criteria (targets) in the following Section II. Next, the specialties of the three approaches are analyzed based on their product life cycle in Section III. Based on these two sections, a selection procedure is presented in Section IV, followed by a case study in Section V. After a discussion in Section VI, this article ends with a conclusion.

II. Targets for Selection

For any selection procedure, it is necessary to define the key targets to be fulfilled by the devices. Common targets often cited are fast time to market, improved costs and competitive advantages [5]. These competitive advantages describe product properties beside the price and differ between application domains. In previous work, we already identified a set of impact factors for hardware platforms [6]. For this work, we take a system view on the control units (electronics + software + mechanical). Moreover, we assume that the functional requirements are fulfilled for industrial environments in case of all candidates. The resulting set of targets is presented in Figure 1 and will be further described below.

A. Time to Market

A fast *time to market* is an obvious target. As soon as the product is on the market, amortization of non-recurrent costs can start. Moreover, a fast *time to market* can be a competitive advantage to competitors.

B. Costs

As with *time to market*, it is an obvious target to keep the *costs* low. However, several aspects have an impact on the overall costs for a product.

In case of *recurrent costs*, it is the cost of purchasing or manufacturing the product itself. In addition, license costs for software (drivers, operating systems, etc.) and/or hardware modules (e.g., inclusion of externally developed modules in custom made products) as well as costs resulting from later maintenance activities have to be considered.

The *non-recurrent costs* for a custom made control unit include development costs (including costs for prototypes and test activities during development) as well as costs for the preparation of the series production (creation and test of tooling, as soldering frames, adapters for automatic assembly, programs for test equipment as automated optical inspection (AOI), in circuit tester (ICT), and/or functional tester, test adapters and specific test electronics). Further non-recurrent costs that also appear for COTS systems are the costs of integration of the electronic control system into the target system as well as those for verification, validation and certification activities (performed before and/or after integration in target system). Often, at least certification activities are executed on system level, but benefit from pre-certified components. Finally, costs resulting from required documentation activities (product + development process) have to be considered.

C. Product Properties

While we assume that all candidates can fulfill the specified functional requirements, further properties could make a difference.

A first important property is the *availability* of the product (availability in this context is not the operational availability but the possibility to purchase or manufacture the product). For any application, it is important that the required control electronics are available for new products and the replacement of defect units.

As many industrial control electronics perform safety and/or mission critical tasks, their *reliability* and *functional safety* is another important factor. As evaluated in previous work, the choice of the hardware platform has impacts on the safety properties of the overall system [7]. The specific needs have to be analyzed for each application individually.

Security is another important property. Especially the increasing interconnection of industrial automation systems via the internet requires corresponding measures [8], [9], [10]. Additionally, a protection of the *intellectual property* (IP: firmware, electronics, design, etc.) is often desirable to protect own products from plagiarizing. As with functional safety and reliability, the requirements depend on the individual application.

For applications that evolve during their life time (e.g., an industrial plant undergoing modernization) or those in which a control unit should be applied in several different target applications (perhaps not all of them defined today), it is desirable to work with systems that can be *adapted* to different or changing requirements. Examples are modular PLCs which allow to add a variety of different plug-in modules (analog and digital I/O, communication interfaces, special function modules). Another approach is to define major parts of the product via software or reconfigurable hardware (e.g., FPGAs).

While *energy efficiency* of control units was predominantly an issue in mobile and battery powered devices in the past, it is now also an issue in all industrial application (especially if a high number of control units is applied). Additionally, *size* and/or *weight* is an issue in several applications.

Sustainability in this context describes environmental aspects in the life cycle of the product. The increasing number of electronics produced every day comes with an urge to think about resources and recycling. In the area of resources, relevant questions are for example the following: Is it feasible to reduce the amount of energy needed for the creation of a product? Is it possible to use sustainable resources (e.g., material of natural origin, as described for example in [11]) and to avoid critical materials (an example is the ROHS directive [12]). Recycling on the other hand deals with options to reuse parts and materials from old electronics at the end of their life-time.

D. Customer Perception

Another target that could be important is the customer perception. While a decision could not be the optimum choice, it still might be the optimum solution from the customers perspective. As an example, the use of a COTS device with a good reputation might increase customer's confidence in the product although it does not differ from alternatives from a technical point of view.

E. Legal and Regulatory Requirements

Finally, legal and regulatory requirements have to be considered for every product. These requirements have effects on product properties (for example on safety properties) as well as on the overall development and production process (e.g., safety standards require certain development processes). To follow all given requirements becomes especially critical if the product should be sold in several different countries (e.g., Europe, US, and India). There is strong effort to harmonize the different standards and regulations present all over the world, but today one still has to deal with differences between countries. Thus, at least the selection of countries in which the product should be sold later on has to be considered as a target in the selection process.

III. Product Life Cycle

In this section, a typical product life cycle is presented for a design based on COTS control units, a design with CM control units and a combination of COTS and CM components.

Following accepted processes, the product life cycle starts with a specification. While the creation of a sound specification

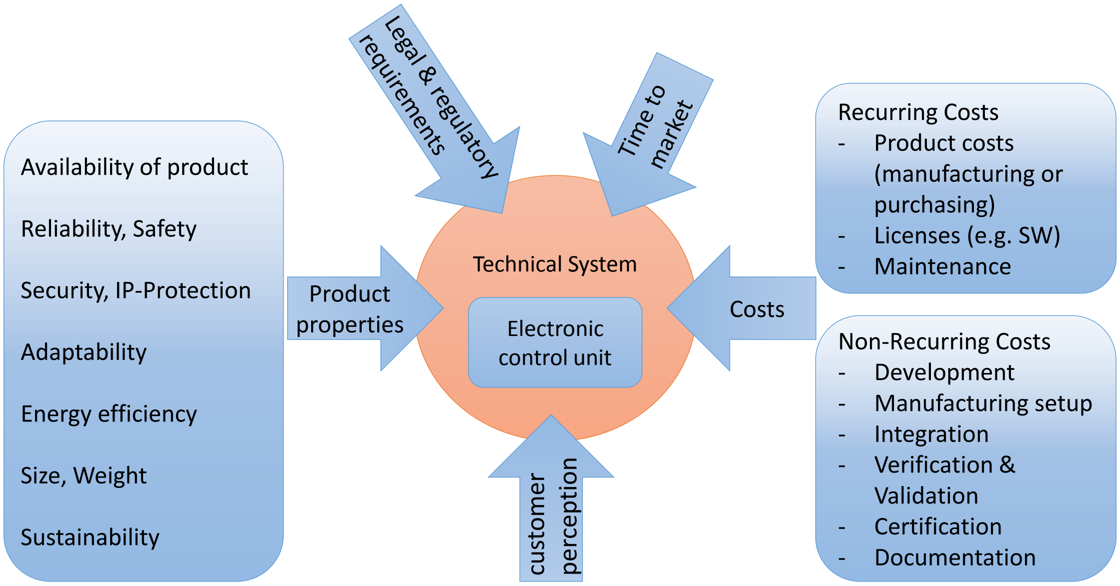

Figure 1. Targets for selection of electronic control units

is a major task, we assume it is already existent for the next step. Nevertheless, it has to be noted that specifications are often not fixed in early phases. While a first approach typically includes the complete "wish list", first concepts based on the early specification often show that targets (mostly costs) cannot be reached. Therefore, typically several iterations of specifications and corresponding concepts are required to create a practicable specification (see Figure 2), especially if new and unfamiliar approaches and techniques are applied. It is expected that also in this phase of creating the specification, differences between COTS and CM components are present (for example, concepts for first estimations are probably easier to establish with COTS components than on basis of a CM design). While the impact on the specification might be a further interesting difference between COTS and CM approaches, it is outside the scope of this article. Therefore, it is assumed that a suitable specification is present for the remaining article.

Based on the specification, an implementation could be realized in the three ways presented in Figure 3.

1) For a CM approach, development activities are required followed by integration, verification, validation and certification. In parallel, the manufacturing set-up has to be established and verified.
2) In case of a COTS approach, development activities are replaced by a selection and qualification of suitable COTS devices. In this case, no production activities take place.
3) A combination of COTS and CM devices includes the elements of both life cycles, CM and COTS.

In all three cases, the aforementioned activities are followed by operation, maintenance and repair activities.

Industrial control systems have a long useful life that requires *life cycle services* (examples are maintenance, modifications and retrofit). According to a publication by the international society of automation, only 20-40% of the investment for an automation systems is spent on the purchasing of

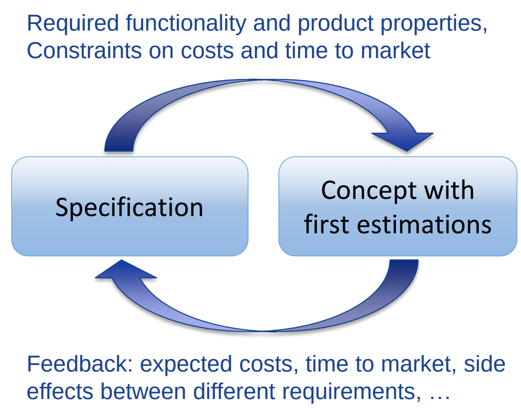

Figure 2. Typical iterations during creation of the specification

the system while the remaining 60-80% are required for life cycle services [13]. Accordingly, these activities are of great importance for industrial applications and should be kept in mind during the selection process.

Finally, each product life cycle ends with some *end of life* activities, typically decommissioning. As the impact of this phase is considered low for the selection process, end of life activities are not considered in this article. The following subsections deal with the specific characteristics of the three approaches.

A. COTS

In case of a COTS design, a suitable device has to be selected. The aim is to identify an existing product that fulfills the requirements given in the specification. Moreover, further aspects as those presented above could be important for the selection, although often not explicitly stated in the specification. Depending on the application, it might be useful to reconsider the specification, if no suitable COTS device could

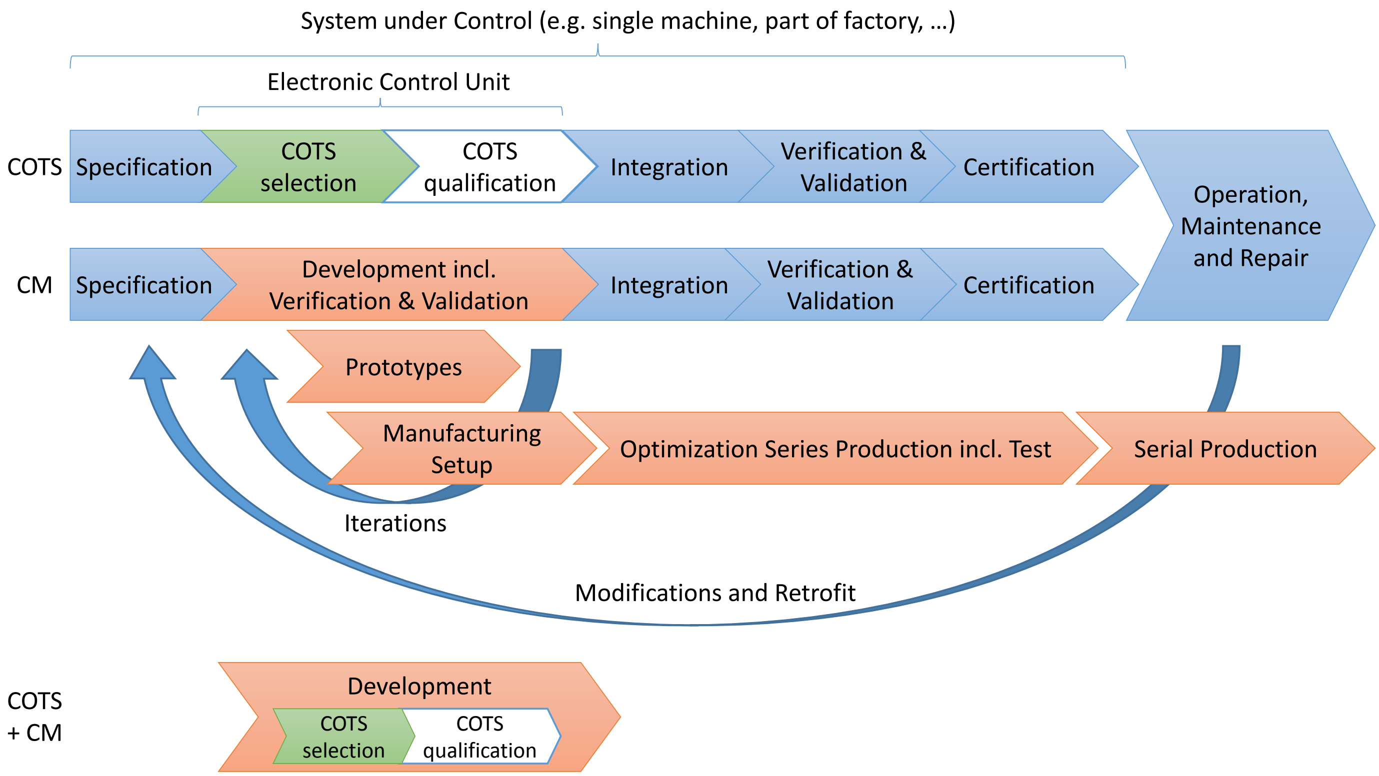

Figure 3. Product life cycle for different approaches (length of phases does not necessarily reflect the effort required for this phase)

be identified. Moreover, the fulfillment of the requirements is often not only determined by the product itself and related aspects (e.g., documentation), but also by the relationship to the supplier of this device (support during integration, operation, maintenance, long time availability, insight into verification and validation activities, willingness to perform further verification and validation activities if needed, etc.). Especially for critical applications, additional verification activities could be required to apply COTS devices (see [2] as an example for military applications). If these verification activities are required and cannot be performed by the supplier, own verification activities have to be performed with the COTS device.

In the next phase, the selected COTS device has to be integrated into the application (for this approach, we assume that no modifications are required to integrate the COTS device). In this phase, the knowledge of the COTS device's properties is of great importance. Gaining this knowledge could be time consuming, but could be eased by support given by the supplier (good documentation, qualified hotline support, tools supporting integration, etc.).

While verification and validation of the control unit itself has already been targeted, it is the overall system that has to fulfill the requirements. Thus, verification and validation activities have to be performed also on system level. Based on the application, also certifications are required or recommended (e.g., functional safety applications). Several COTS devices come with some pre-certification for certain applications (as the mentioned safety applications). These pre-certifications typically ease the certification activities on system level.

B. Custom Made

The CM approach requires development (including all design, implementation and test activities to reach a suitable prototype) and manufacturing activities. During development, prototypes are implemented and verified on basis of the specification. Design decisions have to consider functional aspects, as well as further impacts (see Figure 1). Some aspects for COTS apply here for specific integrated circuits used in the design. They can simplify design and verification activities, but also lead to the challenges listed in the COTS section (e.g., availability). Especially in complex designs, often several prototype stages are required until verification and validation activities are passed successfully.

Additionally, an ideal design is optimized for later manufacturing as these optimizations can significantly reduce manufacturing times and tooling costs. Generally speaking, the aim is to deal with the complexity in development and manufacturing [14]. For optimum time-to-market, the preparation for manufacturing is started before the development activities are finished. The required synchronization between development and manufacturing activities are often challenging [15]. Moreover, to determine the start time of preparation activities, the following tradeoff is necessary. On the one hand, the risk of changes in the product that are relevant for production has to be kept low (ideal: wait until everything is definitely working as specified). On the other hand, a late start of preparation activities is resulting in negative impacts on the time to market and/or a reduced preparation time.

In the following steps, optimizations of the manufacturing process take place, mostly to optimize manufacturing time and quality. Integration, verification and validation activities can start with prototypes, but final tests and certification typically require first samples from the serial manufacturing process.

In case of a COTS product, analysis of defect products, obsolete components or changes in regulatory requirements (e.g., EMC requirements) are typically performed by the supplier. Also in case of a CM design, this analysis has to be performed periodically to check if changes in the product are required. While these activities could be outsourced, the effort for these activities has to be considered. Moreover, required changes could result in costly redesign activities (new verification, validation and certification activities might be needed), a risk worn by the supplier in case of COTS components.

C. Combination

The process of combining COTS components with a CM design follows a combination of both processes. Typically, the product core is implemented with a COTS component and the interfaces are custom made, but also other parts as interfaces or power supplies can be implemented with COTS parts. Thus, during development all aspect of a CM design have to be followed in addition to a selection of suitable COTS components (lower part of Figure 3, only the differences to the CM process are displayed).

While the use of COTS components comes with some challenges to be considered (see section above), it can simplify the remaining development significantly. An example is the use of a COTS single board PC on a custom made printed circuit board (PCB) populated with interface and power supply circuits (and some application specific functions if needed, see also Section V). This combination can simplify the manufacturing process if the main PCB is populated with comparatively simple components only (e.g., easy assembly, no extra small structures on PCB). Furthermore, PC parts as memory chips tend to become easily obsolete, a problem now covered by the supplier of the PC board. For the supplier of the PC board this problem is less critical, as he typically benefits from higher production volumes (boards are sold to many customers). Thus, the resulting price of buying the PC modules could be lower than to manufacture low quantities in house.

IV. Selection Procedure

The combination of the targets presented in Section II and the product life cycles presented in the preceding Section III provide the basis for a systematic selection. The consideration of the many factors presented above leads to a so called *multi-criteria decision analysis* (MCDA) [16], [17]. MCDA offers several different approaches for a systematic decision, one will be described in the following. For all approaches, it is necessary to establish an objective evaluation. Therefore, it is recommended to evaluate each factor in a team (at least technical and sales representatives) to consider different viewpoint in the decision process.

An example for a decision procedure is displayed in Figure 4. Each selection procedure should start with a sound requirements analysis. As a result of this analysis, functional requirements should be defined as well as **all** required targets (see Figure 1 for detailed targets). The following analysis of design alternatives is then based on these requirements as well as on the corresponding life cycles (see Figure 3).

In case a CM design might be the desired choice, experts from the area of electronic development and manufacturing should be consulted (internal or external partners). This way, quantitative data can be achieved for costs and time-to-market aspects. However, for reliable data, a sound specification and ”trustworthy” experts are required.

Besides costs and time to market, the targets are of qualitative nature. While a qualitative analysis is probably sufficient in many cases, a rating system can be applied in case of all qualitative aspects (e.g., rating of products availability from 1 to 10) if needed, for example in form of a decision matrix. Rating can be agreed on in the team or it can be build from a set of individual ratings. An example for such a decision matrix can be found in Figure 5. On the left, quantitative aspects of three different devices are evaluated. On the right, the qualitative aspects are rated based on the rating proposed above. It is important that a consensus should be found within the decision team for each result. In Figure 5, all targets are considered as equally important and no weighting has been applied. In the case that differences in the importance of the targets exist, a weighting can be applied as presented in Figure 6. In this extended approach, the rating of each target is multiplied with the weighting factor (with 1 for the lowest importance and 9 for the highest importance) in the column W·R. Obviously, this weighting can have a significant effect on the result (in the given example, the COTS approach now outperforms the CM approach). The impact of the importance of the different targets is further discussed in Section VI.

During the evaluation, it will become obvious that the results within the targets have dependencies with the costs (e.g., reliability can be typically approved by additional measures. However, these measures typically have an impact on the costs). Thus, every change in the concept should be evaluated concerning it’s impact on other factors (especially cost). If a consensus is found on the results for all targets, a sound decision is possible between design alternatives.

V. Case Study

In this section, three existing control units are evaluated based on the criteria defined before. The emphasis of the following description is on the properties of the selected system and not on the selection process (devices already exist).

A. Three Control Units

The following control units are considered for the presented case study:

1) A machine for sorting metal parts: The control unit is required to switch electric motors and pneumatic valves and read several position sensors and an analogue input for measuring the metal parts. Moreover, the status of the machine has to be displayed on a screen. The expected volume required of this machine is ≤ 50 units per year.
2) A user terminal for an embroidery machine: The control unit has to read the required embroidery pattern from a USB stick and display it on the screen of the terminal. Moreover, user commands have to be read from the terminal. A set of commands is computed and send to the embroidery machine via a proprietary interface. The expected volume is 800 units per year.

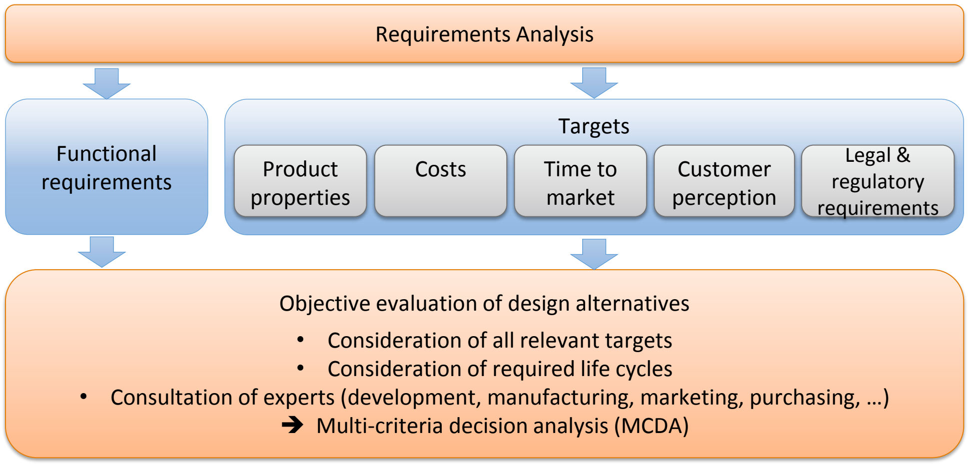

Figure 4. Proposed selection procedure

	Alternatives :	A	B	C
	Type :	CM	CM+COTS	COTS
	Targets ↓			
Costs Recurring	Product	100	250	500
	Licenses	0	0	0
	Maintenance	0	0	0
Costs Non-Recurring	Development	150000	50000	0
	Manufacturing Setup	50000	30000	0
	Integration	3000	4000	5000
	V&V	10000	10000	5000
	Certification	7000	7000	4000
	Documentation	2000	2000	1000
	Σ	*222000*	*103000*	*15000*
Σ	100 units	232000	128000	65000
Σ	500 units	272000	228000	265000
Σ	1000 units	322000	353000	515000

	Alternatives :	A	B	C
	Type :	CM	CM+COTS	COTS
	Targets ↓			
Product Properties	Availability of product	9	6	5
	Reliability & Safety	6	6	6
	Security & IP-Protection	7	7	7
	Adaptability	9	9	7
	Energy efficiency	8	8	8
	Sustainability	8	7	7
	Size & Weight	8	7	7
time to market		4	6	9
legal & regulatory requirements		8	8	9
customer perception		8	8	7
Σ		75	72	72

Figure 5. Example for MCDA based on decision tables

		Alternatives :	A		B		C	
		Type :	CM		CM+COTS		COTS	
Targets ↓		Weighting ↓	Rating	W ·R	Rating	W ·R	Rating	W ·R
Product Properties	Availability of product	7	9	63	6	42	5	35
	Reliability & Safety	8	6	48	6	48	6	48
	Security & IP-Protection	7	7	49	7	49	7	49
	Adaptability	4	9	36	9	36	7	28
	Energy efficiency	8	8	64	8	64	8	64
	Sustainability	8	8	64	7	56	7	56
	Size & Weight	1	8	8	7	7	7	7
time to market		9	4	36	6	54	9	81
legal & regulatory requirements		9	8	72	8	72	9	81
customer perception		4	8	32	8	32	7	28
Σ			*75*	**472**	*72*	**460**	*72*	**477**

Figure 6. Example decision table with weighting of targets

3) A control unit for automatic domestic windows: This electronic unit has to control a DC motor (PWM, encoders) based on sensor information and information received via a proprietary bus interface. Moreover, the available space for this device is limited to 100x40x18mm. The expected volume here is ≥ 1000 units per year.

B. Evaluation

An overview of the evaluation can be found in Figure 7 while details will be described below. The target *sustainability* as well as *legal and regulatory requirements* were not formulated at the time of this case study and are not considered for this reason. Nevertheless, no changes in the results are expected (no specific requirements for sustainability or legal and regulatory requirements to be covered by the product are given). A general discussion of potential impacts of these two targets can be found in Section VI.

1) Case A: The low quantity of required products indicate a COTS device as best choice. However, a conflict could arise from the remaining targets which are evaluated in the following.

The non recurrent costs, as well as the required time to market clearly benefit from the use of a COTS component. The recurrent price is probably higher than a CM approach, but a quantity of 50 units in most cases does not allow to amortize non recurrent costs for a custom made design including verification.

In addition, product properties have to be considered. Size and weight targets, which could be a tough challenge for COTS approaches, are not critical in this application. The same is true for the energy efficiency of the control unit.

For this application, a modular programmable logic controller (PLC) has been chosen. This approach allows to adapt the control units in case of later changes (e.g., by changing or adding I/O modules or special function modules). Moreover, this approach allows to use similar approaches in different machines (same core unit but differences in modules used).

During the selection of the device, the availability of this device or potential replacements is crucial. Well established systems as well as individual contracts can mitigate the risks. Additionally, the use of standardized components (including the programming languages) ease the migration to alternative systems when needed.

Finally, no specific safety, security or reliability requirements were given in this application. Nevertheless, specific PLC systems targeting these requirements are available.

Based on this brief evaluation, a COTS approach is the optimum solution for this application.

2) Case B: In this application, the need for a proprietary interface requires at least some CM design. Moreover, the visualization requirements for the terminal screen require a certain amount of processing power.

In this application, a combination of a COTS processor board was chosen in combination with a custom made main board implementing the power supply and required interfaces. The use of the COTS board was driven by the following aspects:

- This approach simplifies the design and the manufacturing of the main board (no fine pitch components and less high speed design required o this board).
- For the required quantities, the COTS board has an attractive price compared to the CM approach.
- Components as memory chips change frequently. In the COTS approach, the qualification of new chips is done by supplier.
- An approach of a complete COTS user terminal in combination with an interface converter (required for the proprietary interface to the machine) was resulting in a significantly higher product price.

Furthermore, the remaining cost related factors show no disadvantage of this approach compared to a full custom made design. With respect to time to market, this approach benefits from the COTS components in comparison to the CM approach, as a major part of the design could be implemented as a pretested module. The product properties are influenced as follows:

As the COTS board has a major impact on the availability, a long term contract was set up with the supplier. Nevertheless, a migration to another processor board is possible (probably involves redesign).

Reliability analysis is possible as the complete design including all components is known. Optimizations in the architecture or the applied components could have been performed if required, as well as the implementation of safety functions on the main board.

A protection of the program memory is supported by the processor, no further security or IP protection requirements exist. Adaptability can be achieved by modifications of the main board. However, this approach requires redesigns (incl. verification activities). In this application, it is expected to handle all modifications via SW.

Customization allows optimization of energy, size and weight properties. However, none of these are considered as critical for this application.

Finally, a CM design allows significant separation from competitors (customers perception). In summary, the application benefits from the chosen combination of COTS and CM components.

3) Case C: Size and product price restrictions are major impacts for this application and could not be fulfilled with available COTS components.

The non-recurring costs for the required design and manufacturing activities are significantly higher than with a COTS approach, but could be amortized by the expected quantity in an acceptable period. Costs for verification and certification activities could be held on a moderate level as the complete system was already undergoing sufficient procedures.

With full control of HW and SW design, specific project properties (e.g., proprietary bus interface, protection of firmware, emergency stop, life beat) could be fulfilled. Finally, the time to market was (with almost a year) long compared to a COTS approach, but not critical as the development of the complete system took a similar amount of time.

	Case :	Case A	Case B	Case C
	Description :	Machine for sorting metal parts	User terminal for embroidery machine	Window control unit
	Assumed annual quantity :	≤ 50	800	≥ 1000
Targets ↓ Choice →		**COTS**	**COTS + CM**	**CM**
Costs Recurring	Product	high, but according to low quantity best with COTS device (here PLC)	combination of a COTS processor board with a custom made main board allows a competitive product price	custom made design allows cost optimized approach (for given constraints)
	Licenses	no licence for operation	open source operating system	none
	Maintenance	diagnosis features supported by PLC, modular PLC allows replacement/ repair of modules	individual repair/replacement of processor and main board possible, maintenance features have to be custom made	diagnosis features implemented via bus interface
Costs Non-Recurring	Development	HW: only selection & integration SW: based on PLC operating system => application only	HW: only main board + selection processor board & integration SW: operating system has to be adapted to custom design + application SW	full development of electronics and software
	Manufacturing Setup	none	manufacturing of main board + integration processor board + test in manufacturing; separate processor board, no fine pitch devices on main board => simplifies manufacturing process	full manufacturing setup incl. test required
	Integration	HW setup with COTS IDE + wiring of sensors and actuators	1) main and processor board 2) operating system and HW 3) application	HW/SW integration in development, integration with remaining system via bus interface
	V&V	focus on SW + overall system	complete system	complete system
	Certification	not required for control unit	EMC test for CE marking	EMC test for CE marking, further tests with complete system
	Documentation	SW + wiring (hardware configuration saved in project data)	full documentation, exisiting documentation for processor board and operating system can be included	full documentation
Product Properties	Availability of product	depends on PLC supplier, long term industrial availability provided	depends on supplier of processor board (long term contract), processor board can be replaced (redesign main board + comparable alternative processor board)	depends only on components used, obsolences can be handeld with 2nd source components, if needed in combination with redesign (HW or HW+SW)
	Reliability & Safety	no specific requirements, COTS HW is assumed to be well tested, COTS devices typically = black box, but reliability and safety data is available for certain devices	complete reliability analysis possible for main board, data für processor board available from supplier. No specific safety requirements. (implementation on main board could be an option if required)	complete reliability analysis possible for electronics. Specific safety requirements could be implemented in SW and HW (emergency stop, life beat)
	Security & IP-Protection	supported, setting via COTS IDE	processor supports protection of program memory	processor supports protection of program memory
	Adaptability	modular PLC systems allows to add further modules (I/O, special function, …), other devices can be added via bus interface	full control of SW, custom main board allows adaptations, but these changes require redesigns of the hardware (incl. verification and certification)	full control of SW, full control of HW, but changes require redesign (incl. verification and certification)
	Energy efficiency	COTS devices with acceptable energy efficiency are available	the custom made design and the selection of a suitable processor board allows an optimized design	stand by <0,4W => low power controller in combination with suitable HW and SW design (sleep modi)
	Size & Weight	no specific requirements	size of PCB determined by 10" screen (not critical) no specific weight requirements	critical => only achievable with custom design
time to market		fast (weeks)	medium (months), with COTS processor board, the SW development can start before custom made HW is ready, risk of design iterations	medium-high (months), with evaluation board, the SW development can start before custom made HW is ready, risk of design iterations
customer perception		selected brand of COTS device supports image of high quality product	customized solution allows separation from competitors	customized solution allows to meet the targets for size and product price

Figure 7. Case Study

VI. Discussion

In the presented case study, the emphasis is on the differences of the three approaches presented. However, even the simplified description of the selection performed for these case studies shows the advantages compared to an unsystematic approach. The collection and evaluation of the proposed targets in combination with the consideration of the complete product life cycle prevent that important factors are neglected during the decision process. In addition, quantitative approaches as described in Section IV can be applied to further formalize the selection.

Moreover, one could argue that the decision for or against COTS devices is solely driven by the quantity of the required units. For sure, in extreme cases (less than 10 units, more than 100000 units) the decision is probably simple. However, for medium numbers and depending on further targets to be fulfilled by the control unit, the decision process differs. As an example, a product with a quantity of 1000 units/year could be better implemented with COTS (high volume product that perfectly matches requirements) and a unit only needed a few 100 times a year might be better in CM (e.g., when other targets do not allow a pure COTS approach).

Furthermore, it has to be noted that the importance of the different targets could be rated very differently for different applications (An example for a weighting of targets in the decision process has been presented in Figure 6). As the result of the overall analysis depends a lot on this rating, it has to be performed precisely. If, for example, the following targets are rated very high compared to other targets, this rating can have a major impact on the decision:

- *availability of the product:* if a CM design is possible with standard components (all with at least 2nd source), a high independence from suppliers can be achieved by a CM design. This independence could result in a major advantage compared to a COTS approach. However, it has to be noted that it is often not possible to find suitable 2nd sources for all components of a product. Examples for critical components are microcontrollers and all other specific integrated circuits, displays and specific connectors. Nevertheless, an option to reduce the risk of unavailability for the components without a suitable 2nd source is to set up delivery contracts with the suppliers of these components.
- *safety and adaptability:* if a control unit including safety functions should be open to later adaptations, the effort for later changes (concept, implementation, verification, validation and certification) could be significantly lower in case of a well supported COTS device.
- *legal and regulatory requirements - device should be sold worldwide:* Depending on the product, this requirement could result in a high effort, especially in case of certification activities. If COTS devices with the required certifications are available (or can be made available by the COTS supplier), this target can be met easily by choosing the COTS approach.
- *sustainability:* If specific sustainability requirements are given (e.g., high percentage of the material used in a control system should be recycled at the end of product life, overall energy footprint of the manufacturing of the device should be below a certain threshold), the set up and implementation of the recycling concept can be challenging. As with the requirement above, a COTS approach can simplify the effort to reach this target IF a COTS device with the required properties is available.

VII. Conclusion

The comparison of COTS and CM approaches (or combinations of both) requires more than just an analysis of cost and time to market. In addition, the overall costs (recurring and non-recurring) are compiled from several aspects and not only the cost of the control system itself. Therefore, a set of important targets to be considered in the decision process has been presented in this work. These targets include different types of costs, time to market, legal and regulatory requirements, customer perception as well as large set of product properties. The considered costs are compiled from recurring costs (for product, licenses and maintenance) and non-recurring costs (for development, manufacturing setup, integration, verification, validation, certification and documentation). The presented product properties include availability, reliability, safety, security, IP-protection, adaptability, energy efficiency, sustainability, size and weight. Moreover, impacts on the product life cycles of the different approaches have been discussed. Based on these two aspects (targets and impacts on life cycles), a systematic selection process for industrial control systems has been proposed. The proposed process includes MCDA and allows to apply quantitative approaches to further formalize the selection. Finally, the selection process has been demonstrated in a case study with three industrial control units.

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