COTS or Custom Made? Design Decisions for Industrial Control Systems

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***Abstract*—In the area of industrial control systems, the choice between *custom made* (CM) electronics and the use of *commercial of the shelf* (COTS) components is often not trivial. Especially, when required quantities or specific requirements do not give a clear sign for selection. From a pure cost point of view (development costs and product costs) a decision might look trivial, but a broader view helps to perform an sound decision. In this work, decision criteria and a decision method are presented for industrial control systems targeting COTS devices, CM devices or 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**

I. INTRODUCTION

In industrial automation, commercial of the shelf (COTS) components as programmable logic controllers (PLCs) and industrial PCs (IPCs) are widely used as control units (For this paper, we follow the following definition for COTS: A COTS device can be bought from a catalog without modifications [1]). 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. In other application, a change from a custom made design of control units to COTS components is discussed.

A custom made development often comes with an optimized functionality and an attractive price of the final product, but involves much more than own 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 changes (e.g., obsolete memory chips require replacement).

On the other hand, the use of COTS components often requires more than applying a plug and play procedure. In the example of COTS components in critical applications, it could be required to establish specific relationships with the suppliers and/or to perform additional tests on the COTS components (examples can be found in [1]).

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) [2] that aims to consider all cost factors of a product during product life. To supplement existing approaches with the required technical data, this paper deals with the differences of the following approaches for industrial control units:

1) Commercial of the shelf (COTS)
2) Custom made (CM)
3) Combination of 1 and 2.

The main focus of this paper is on electronic control units (including their software), but not on pure software products as discussed for example in [3].

As a basis for a systematic selection procedure, we collect relevant selection criteria 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, the paper ends with a conclusion.

II. TARGETS FOR SELECTION

Before having a closer look on the different approaches, 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 [4]. 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 [5]. 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 impacts 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

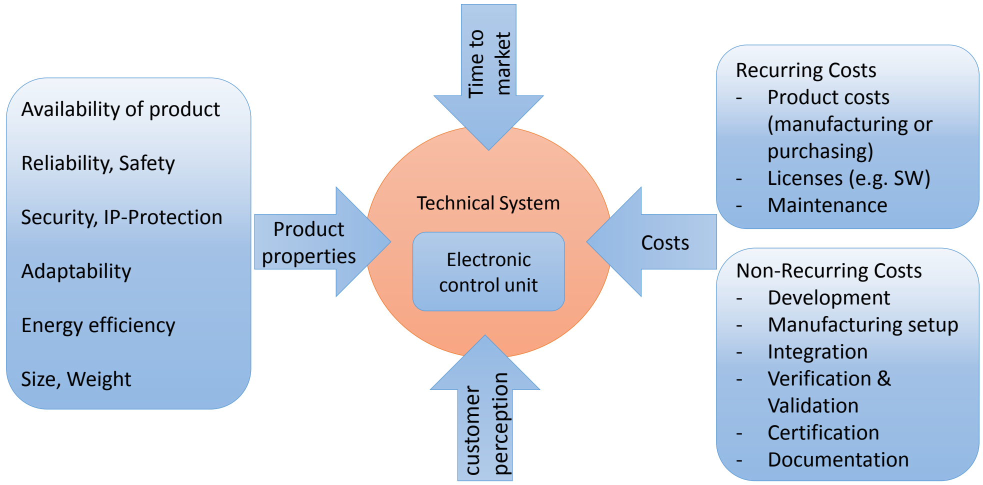

Figure 1. Targets for selection of electronic control units

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 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 replacements 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 [6]. 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 [7], [8], [9]. 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.

D. Customer Perception

Finally, an impact 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.

III. Product Life Cycle

In this section, a typical product life cycle is presented in Figure 2 for a design based on COTS control units, a design with custom made 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 is a major task, we assume it is already existent for the next step. Based on the specification, an implementation could be realized in the three ways presented above. Additionally, 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 paper. The following subsections deal with the remaining phases for the three approaches.

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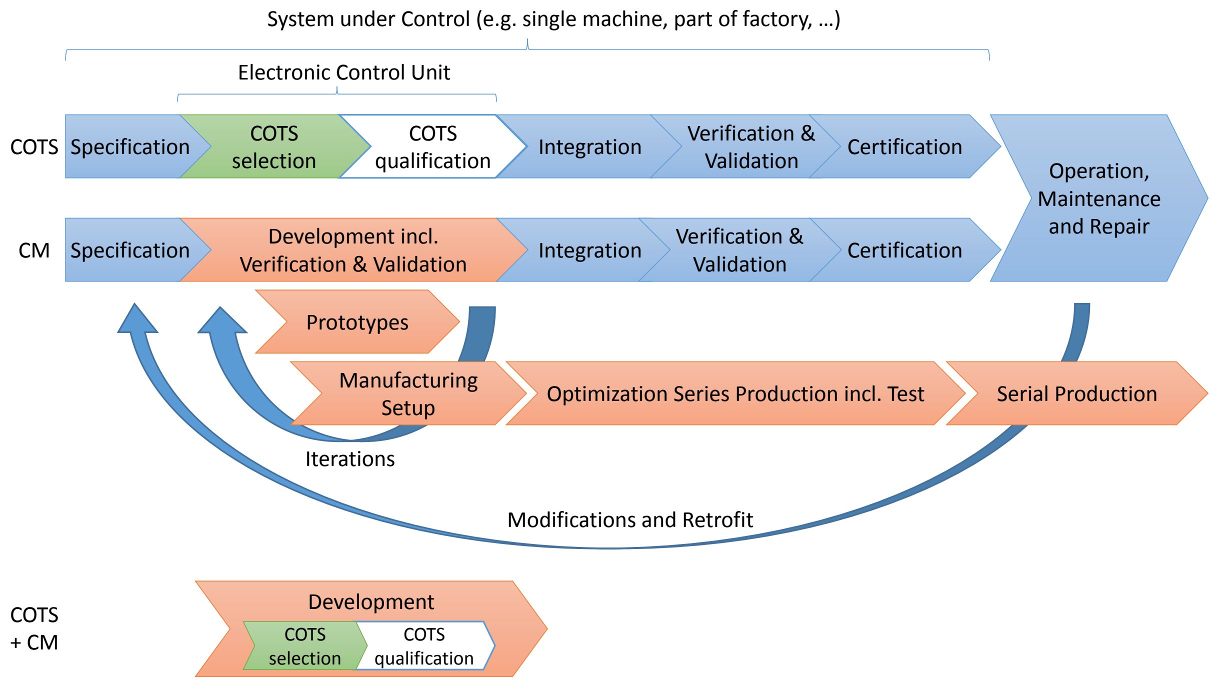

Figure 2. Product life cycle for different approaches (length of phases does not necessarily reflect the effort required for this phase)

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 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 [1] 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 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 reducing manufacturing times and tooling costs. Generally speaking, the aim is to deal with the complexity in development and manufacturing [10]. 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 [11]. Moreover, to determine the start time of preparation activities, a tradeoff between risks of changes in the product relevant for production and reduced preparation time is necessary.

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.,

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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 custom made 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 custom made design have to be followed in addition to a selection of suitable COTS components (lower part of Figure 2, 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. Furthermore, PC parts tend to become easily obsolete, a problem now covered by the supplier of the PC board. But the supplier of the PC board benefits from his high production volume. Thus, the resulting price of the PC module could be lower than to manufacture low quantities in house.

IV. Selection Procedure

Based on the targets presented in Section II and the product life cycles presented in the preceding Section III, a systematic selection is feasible. For an objective evaluation, it is recommended to evaluate each factor in a team (at least technical and sales representatives). In case a custom made 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. Further approaches for these so called *multi-criteria decision analysis* (MCDA) can be found in literature (e.g., [12]).

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

1. 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 volume of this machine is ≤ 50 per year.

2. User terminal for 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 volume is 800 units per year.

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

B. Evaluation

An overview of the evaluation can be found in Figure 3 while details will be described below.

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. 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 custom made approach, but a quantity of 50 units in most cases does not allow to amortize non recurrent costs for a custom made design incl. verification. Finally, product properties have to be considered. Size and Weight targets, as well as energy efficiency, which could be a tough challenge for COTS approaches, are not critical here. 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. Moreover, this approach allows to use similar approaches in different machines. 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. However, 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 custom made 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:

- simplifies design and manufacturing of main board (no fine pitch components, less high speed design)
- in required quantities, COTS board has an attractive price compared to CM approach.

	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 3. Case Study

- components as memory chips change frequently. In 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 was resulting in a significantly higher product price.

Also 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 is known. Optimizations 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, non of these are considered as critical here.

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

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 could be fulfilled. 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 similar time.

VI. Discussion

While the emphasis of the presented case study is on the differences of the three cases, the compiled data can be used as the basis for a systematic decision process. Even in a pure qualitative approach, the collection and evaluation of the proposed targets and the consideration of the design process prevent that important factors are neglected during the decision process. If required, quantitative approaches as described in Section IV can be applied to further formalize the selection.

A first impression could be 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). Additionally, the importance of the different targets could be rated very differently for different applications. If for example the availability of a product is rated very high and CM design is possible with standard components (all with 2nd source), a high independence from suppliers could be achieved by a CM design.

VII. Conclusion

Comparing COTS and CM approaches (or combinations of both) requires more than just an analysis of cost and time to market. Moreover, the overall costs (recurring and non-recurring) are compiled from several aspects. This paper presents a set of important targets to be considered in the decision process, as well as impacts on the product life cycle of the different approaches. A systematic selection process can be based on this evaluation as demonstrated in a case study with three industrial control units.

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