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A Resilient and Time-Efficient Approach to Product Development Through Availability-Based Design (ABD)

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Abstract

The conventional design process (CDP) considers availability issues at the latest stages of the overall machine design project. Designers' contributions are focused on technical and quality aspects. In most instances, other teams within the supply chain address delivery issues separately. Yet, current machine design projects are severely bound by deadlines, volatile, and sometimes uncertain. Due to the iterative nature of the design process itself, the number of potential design combinations is large. Their inherent technical checks and evaluations are highly time-consuming. In this paper, to avoid unnecessary design effort, the availability of components is considered at the early stages of the design process. This paper presents the Availability Based Design (ABD), which reorders the design process steps to preclude achieving a design that would be incompatible with the delivery time constraints. A ball screw drive actuator is used as a reference case study to quantitatively compare the performance of ABD to the CDP. The influence of key parameters is studied, including the availability ratio, the automation of key steps of the design process, the number of families of components and the number of technical checks necessary for validating a design. The performance assessment shows that ABD reduces the design time for availability ratios below 0.8 in manual design, and that automating the method makes ABD systematically faster than the CDP.

Keywords: machine design; availability-based design; design process

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1. Introduction

By nature, design is considered one of the most complex processes as it requires meeting antagonist constraints [1–8]. The design problem is only solvable by iterative approaches (as discussed in the case of guided iterations by Dixon [9]), with each iteration improving the design with respect to the specifications: the more iterations, the more refined the final design. Any iteration takes the designer time to establish. Any design must be checked for a large number of specific technical parameters, which also demands valuable time from designer (e.g., Spinnler lists over 210 design recommendations to the machine designer in seven engineering segments [10], Childs relates an effective methodology to integrate a large amount of design constraints [11]).

Moreover, the number of technical justifications increases in modern designs [10,12–15]. Spura et al. discuss the continuously increasing need for numerical tools for approaching solutions in design problems [16]. Selecting the right components remains overly complex [1,17–29]. Singh presents the different general design types depending on the industry and focus taken, making clear the origins of this complexity [30]. Polak and the VDI 2234 standard discuss the impact of the cost on design at the component selection steps [31,32], and Ehrlenspiel et al. quantitatively evaluate the impact of the designer's choices on the whole value chain of a given design [33].

Even though some authors mentioned delivery time as a potential design specification or a qualitative attribute [1,3,10,15,17,34,35], none consider it as a primary design parameter. They either neglect to provide a detailed exploration or to propose a methodology for quantitatively integrating this attribute into the design process. Paetzold, and Lebouteiller et al. consider delivery time as an attribute to be estimated, a fortiori, by comparison with similar design cases [36,37].

Nowadays, the economic challenges [38–40], the fast developing markets, the strong pressure on costs (manufacturing, stock, design [39,41–44]), the lack of (experienced) resources [45,46] and the increasing need to document any design comprehensively [4,47–49] clearly compel designer to only design what will actually be available with respect to specifications and time to market.

Although the literature is rich in innovative methodologies for improving design in certain situations, these approaches can be grouped into three main categories: design-centric methods, process-centric methods, and supply-chain-centric methods.

Design-centric methods focus on the product's intrinsic features (e.g., safety factors, manufacturability, modularity). The conventional design process (CDP) is developed in Section 3. Design for Manufacturing and Assembly (DFMA) is a well-established approach aiming to integrate manufacturing and assembly constraints early in the design process to reduce production cost, part count, and assembly complexity. More recent reviews [50] confirm that DFMA approaches contribute effectively to improving downstream manufacturing performance; however, they also highlight that DFMA methods are most often applied after concept selection and remain largely centered on cost and process compatibility rather than on time-related or supply-chain constraints.

Process-centric improve the efficiency of the design process (e.g., coordination, knowledge flow, management), encompassing concurrent engineering were design tasks are executed in parallel rather than in sequence. Lean Product Development [51,52] refers to a family of approaches derived from Lean Thinking, aiming at reducing waste and unnecessary iterations in the product development process, notably through front-loading of knowledge, set-based exploration, and delayed commitment.

Supply-chain-centric methods integrate the constraints and opportunities of the supply chain from the earliest stages of design, recognizing that product architecture decisions have profound and lasting effects on logistics, cost, and responsiveness. Recent research [53] emphasizes the joint optimization of product design and manufacturing inventory. Furthermore, mathematical models have been developed [54] to navigate the tradeoff between product performance and Time-to-Market (TtoM). However, while these methodologies successfully link design outcomes to supply chain performance, they remain largely focused on the structural and logistical alignment of the value chain. Consequently, while they improve the interface between design and the supply chain, they do not address the sequence of technical validation tasks within the design process itself.

The availability-based design (ABD) method discussed in Section 4 goes a step further by taking the most critical supply chain output (TtoM/Availability) and elevating it to a primary filtering constraint before technical design effort is expended. It uses the supply chain constraint to define the feasible design space. Therefore, ABD is not merely a Supply-chain-centric method; it is a Design Methodology that explicitly front-loads a supply chain constraint, making it a bridge between the Design-centric and Supply-chain-centric domains. This unique positioning justifies its separate treatment and highlights its novelty compared to existing approaches.

Nevertheless, none of the identified literature entries showed a detailed integration of the availability question of components at early design stage. In the literature found by the authors, the approaches remain "over the wall" ones [17,55]. They postpone the delivery question to the end of the design process or treat it as a supply chain or a sourcing question of an established serial product. Their focus relay on qualitative attributes (e.g., lean processes, concurrent engineering, sourcing strategies) that may improve the overall process without detailing qualitatively their benefits.

A methodology that prevents any designer time waste is therefore desirable to avoid design deadlock in which a valuable design is found to be technically and economically satisfactory, but is not available at the time-to-market (TtoM) expected. This methodology should be effective both for single design projects and serial products..

In this paper, the availability-based design (ABD) methodology is presented. This framework reorders the machine design process into an improved 8-step scheme that minimizes unavailability risks. It provides designers with a series of satisfactory potential design alternatives. The current work is centered on the design process itself (as defined in the VDI2221 standard [18] and related works). It does not address supply chain strategies of products whose design is already established.

The paper is organized as follows: in Section 2, the definitions of usual terms and nomenclature, as well as a general hypothesis underlying the paper are provided. Then, the Conventional Design Process (CDP) and ABD are defined and described, respectively in Sections 3 and 4. Both design processes are qualitatively compared and discussed in Section 5. A ball screw drive actuator case study is then introduced in Section 6, as a basis for a probabilistic evaluation of the success rate of the design processes under part shortages. Section 7 presents a detailed timeline analysis of both processes. The durations of both processes are then compared under several parameter variations in Section 8. Section 9 presents a sensitivity analysis of ABD to is specific parameters. Finally, concluding remarks are presented in Section 10.

2. Definitions, Nomenclature and Hypothesis

The essential terminology used in this article is defined below. All durations are usually expressed in weeks, on a 52-week annual working basis.

- Design: a rationally structured assembly of components that fulfill (a) required function(s).
- Machine sub-assembly (or sub-assembly (SB)): a set of ordered machine components that performs a group of given functions. Machines are composed of different sub-assemblies [2].
- Bill of Materials (BOM): the list of components needed to produce a given design.
- Design iteration (DI): the realization of the design process one time. A design iteration may lead to a solution, multiple solutions, or no solution if the project is not feasible.
- Design option (DO): a design, resulting from a DI, that has passed satisfactorily all technical checks.
- Designer (D): the person who is responsible for the overall design tasks and for achieving the BOM.
- Project manager (PM): the person who requests the design from the designer and who will make use of the design. The project manager specifies the product design

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specifications to the designer. The designer interacts with the project manager and negotiates the design constraints. In this text, PM is considered to be the customer.

- Time to market (TtoM): the amount of time requested by the project manager (here, the customer) to physically deliver the materials included in the BOM, design services being included. Assembly and its delay are under the responsibility of the PM (here, the customer).
- Time to invest (TtoI): the amount of time that the project manager (here, the customer) will take after the reception of the BOM offer to place the order. Between BOM offering and BOM ordering, a given amount of time occurs..
- Total processing time (TPT): the amount of time effectively consumed to physically deliver the design option(s). This includes all tasks needed to achieve the delivery of the goods.
- Design Time (DT): the time used by designers to perform all engineering tasks needed to achieve the BOM, including the verification of component availability.
- Engineering to Order designs (ETO [56]): are designs where the D engineers, manufactures, and delivers the design.
- Standard components: machine elements that are designed and manufactured in such a way that they can be used in a wide range of different applications. They are standard, repeatable, interchangeable, high-volume, high-performance, and low-cost. They also allow a direct geometrical compatibility, usually based on one of their main standardized sizes.

Hypothesis: the current article finds its roots in the detailed design of SB based on standard components. Standard components allow direct manufacture and/or assembly of design(s) shortly after the BOM has been delivered. Additionally, they significantly reduce geometrical compatibility questions between components. For their timely assembly, the question of their availability must be considered.

3. Conventional Design Process (CDP)

The conventional design process (CDP) is summarized in Figure 1: it consists of a sequential approach, made of separated groups of iterative tasks to achieve one given design iteration that will, adequately, satisfy (or not) the specifications. It takes its roots within the VDI 2221 standard [18,57,58].

In Figure 1, the following steps are found: after a need has been expressed, a formal description of this need is established to check mutual understanding between the PM and the D, and to agree on a given working perimeter. After this first step, a concept is developed to address the specifications and is further discussed between the parties. If this concept fulfills the necessary functions, a design is materialized by selecting components that answer the identified functions to varying degrees. Technical checks (TC) are then realized. The TC prove that the selected components are fit for the required service. A synthesis of these last results showing the performance of this design is then established. Synthesis is discussed between the D and the PM. The results of that discussion may lead to further improvements, additional technical checks, or a final synthesis.

Afterwards, the BOM is established. Conventionally, the BOM is transmitted to other departments (it is what is sometimes called “over the wall” approach [17,55,59,60]) to check its availability. Later, the BOM will serve to establish an official quote. The quote is sent to the Project Manager (PM) for evaluation. In the CDP, delivery times are commonly aligned with the PM’s wishes, as they are not known before the final design is finalized. Very often, new design iterations must be started without any further degree of success. After an official quote has been delivered to the PM, an evaluation step occurs. The evaluation usually takes time as it often requires involving other departments (“over the wall” approach) or comparing multiple quotes from different competitors. This evaluation step yields a list of pain points to discuss with the D during the price negotiation. During this final negotiation step, prices, delivery times, delivery conditions, payment terms, packaging, and other terms are reviewed and agreed upon. The termination of this step activates the ordering step: an official order is established, approved, duly signed by authorized staff, and sent to the D. The official order is received by the D and executed: when manufacturing of ordered components is finished, the BOM is released, packed, labeled, and shipped to the PM.

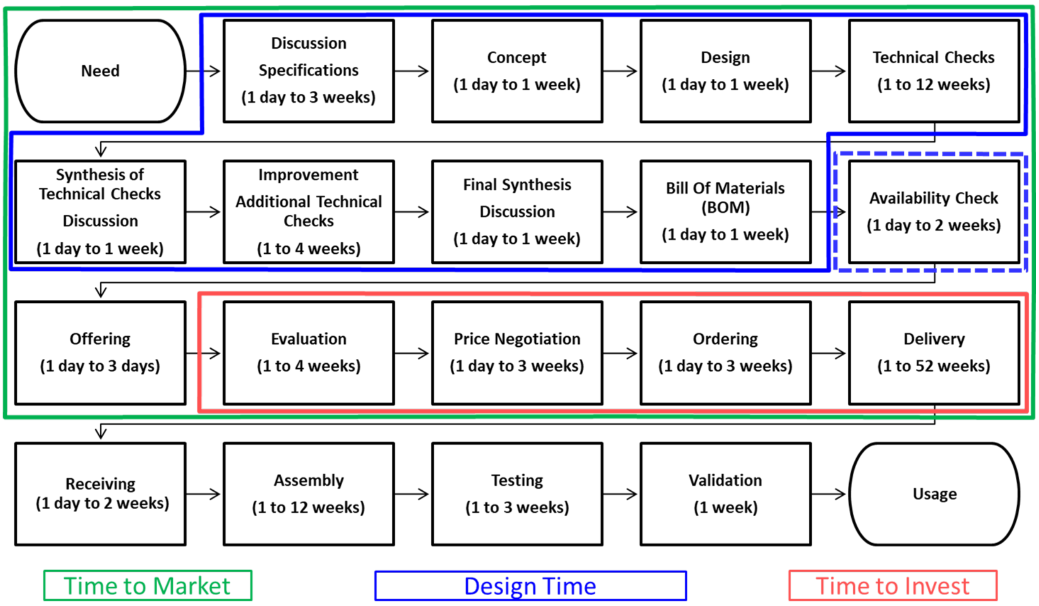

Figure 1. CDP and its main steps (the durations mentioned are examples of average values measured from ETO design practice [61].

The PM receives goods and checks their conformance with the order and the offer. If receiving is approved, the goods are ready for assembly, and the information is released to the concerned departments. Usually, after assembly, tests are performed to confirm the design's viability and characterize its performance. If these tests are positive, validation is complete, and the design is released for public use.

In the context of this paper, the three most relevant durations are as follows:

1. TtoM, which spans between the expression of the need and the delivery of the goods (for a timely, successful design, this last step must be specified). In ETO projects, TtoM depends on agreed deliverables with the D, not necessarily on the market availability of the released design. In that case, TtoM is achieved when the components are duly delivered within the specified timeframe (even if the machine remains unassembled, untested, and unvalidated). The time effectively consumed by the design process to practically provide a given satisfactory design, that is, here, a given BOM of satisfactory components, is the TPT. The design process is successful when TPT $\leq$ TtoM. In the other case, the process fails. In the CDP, availability check and offering steps are usually not done by the D but entrusted to other teams (e.g., internal sales, logistics, customer service).
2. DT, which most accurately quantifies the duration of the D's tasks, including the availability check step (which is particularly relevant for comparison purposes with the other process described in this paper), but excluding the offering step, which is not considered as a design task in the framework of this paper.
3. TtoI, which denotes the duration necessary for the PM to reach the investment decision.

In ETO design, internal statistics pursued over 23 economic segments during the last 20 years show that the TtoM was usually reduced by a factor of 2 per period of 3 to 5 years, while the TtoI followed the opposite trend (multiplied by a factor 2 over the same period) [61]. Under these circumstances, the task of the D is becoming extremely complicated: timely design is clearly at risk.

4. Availability-Based Design (ABD)

The availability-based design (ABD) suggests reordering the main steps of the CDP in such a way that the components' design space is successively filtered for geometrical compatibility, availability, and technical checks. At the end, only the timely successful designs remain. They are technically satisfactory and can be sorted by their performance levels. For this, the concept of Key Design Indicators (KDI) is introduced: KDI sort different filtered designs by given selected performances, e.g., costs, overall dimensions, overall weight, or other selected design properties. KDI are global properties affecting the entire design, in contrast to TC, which address local properties and concern the component itself. Many KDI can be successively checked depending on the performances requested (e.g., overall deformation, cost, overall weight, etc.). Some KDI may be external and shared publicly with the PM, others remain internal and are to the exclusive attention of the D (e.g., margin).

Unlike CDP, ABD brings to the D and the PM a list of the most successful designs, ordered by their KDI. This list of successful designs gives to the D and the PM a further space for discussion, which is not the case in the CDP (e.g., the PM and the D may prefer a given design even if it is not the best, due to previous issues or qualitative appreciation that have not been depicted within specifications, were not clearly and formally described or were forgotten). ABD delivers multiple design options (Replacement designs or design variations) and therefore reduces unplanned risks associated with modern market volatility. In such a way, ABD participates directly in design optimization.

ABD framework is based on eight steps followed by the D. ABD steps are illustrated in Figure 2. Comparing Figures 1 and 2, it is clear that ABD finds its roots in the early availability check for the standard components.

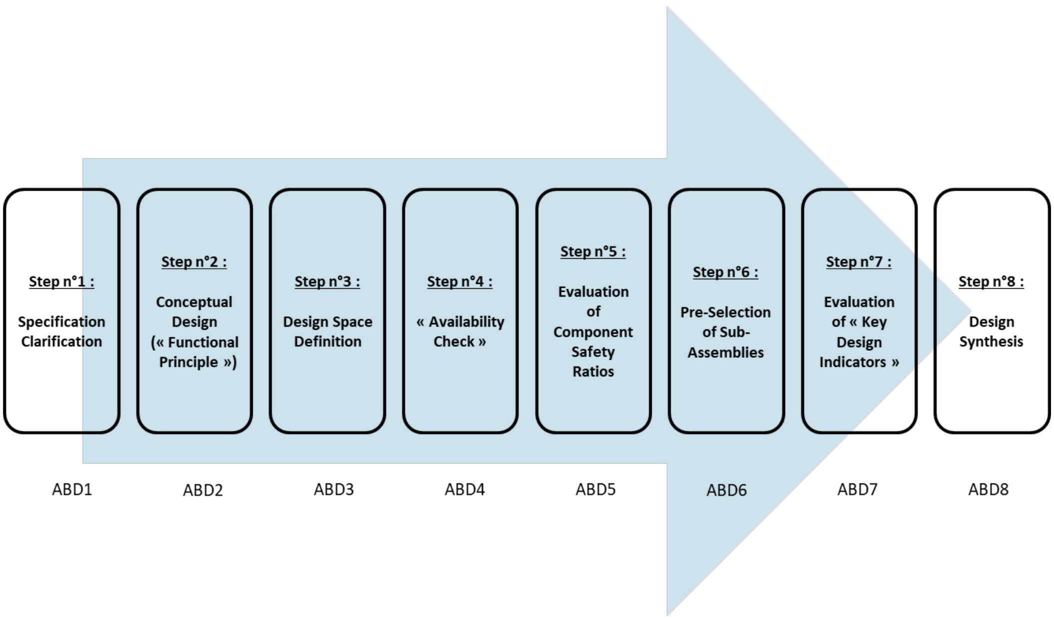

Figure 2. ABD Methodology and its 8 design steps. Availability check of components is performed at the early steps of the design process.

5. Qualitative Comparison of Both Design Processes

The flowcharts of both design processes are compared in Figure 3. The eight primary steps of the ABD are highlighted on the right side, each with its step number. Feedback loops in both design processes represent their inherent complexity. As a brief example, in the CDP, feedback loop 1 is triggered when the concept drawn does not satisfy the specifications. In such a case, no design option can be established. More critically, feedback loops 7, 8, and 9 are needed when the established design option exceeds the budget or delivery time, or when no design option is found. These loops introduce significant complexity and significantly increase the actual TPT and DT. In this figure, the dotted lines indicate that the corresponding loop occurs only in extreme cases. Feedback loops are further discussed in the Appendix A.

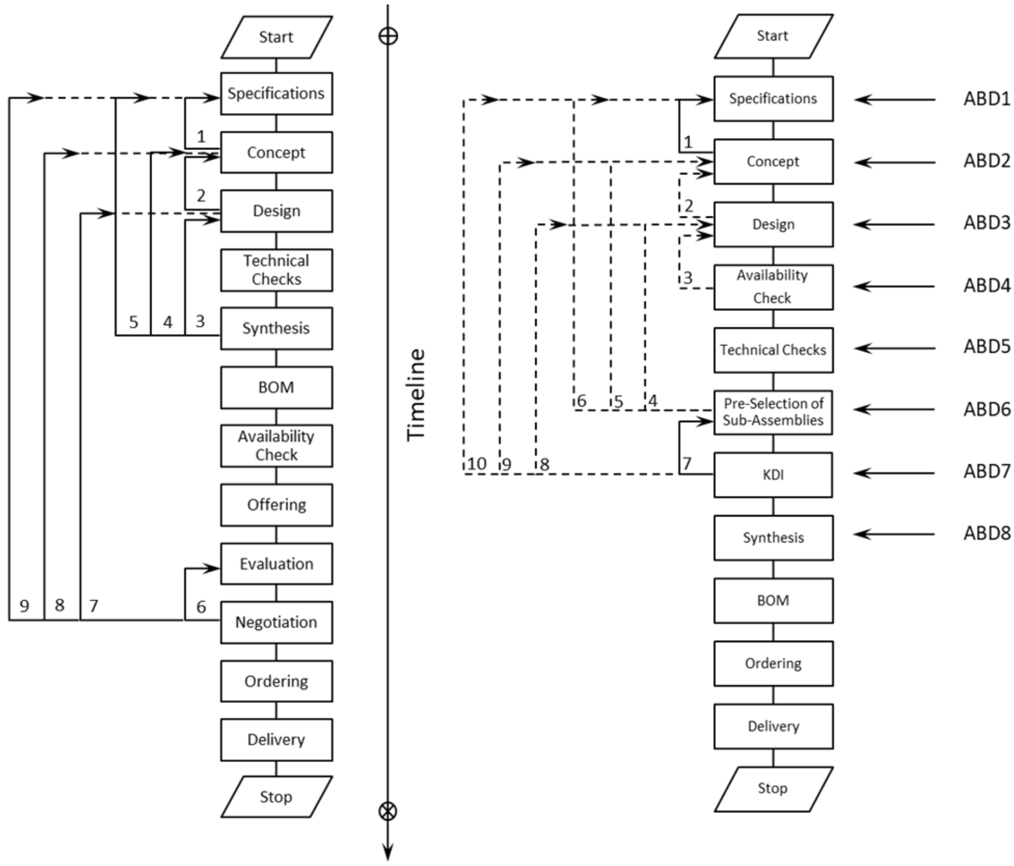

Figure 3. Flowcharts of both design processes: **left**, conventional design process (CDP); **right**, ABD methodology.

In the CDP, a single design iteration is achieved by going through the left flowchart. A DI can lead to a successful DO only when a BOM can be established. At this step, neither the D nor the PM knows if the achieved DO will be available within the specified time limits. This will only be known after the step offering is achieved (“over the wall” approach). It should be noted that the offering step occurs very late in the CDP. Potentially, it can be completed entirely out of the TtoM, which has become particularly sharp in practice.

In contrast, the ABD allows multiple design options, generating available, satisfactory alternative designs. After the concept step (ABD, step 2) is realized, an initial design space of a given number of standard components is selected based on specific criteria (commonly, strength). Immediately after, the availability of the selected standard components is checked. Unavailable components are thus filtered, and only the available components are considered for further steps. A refined design space for the available components in accordance with the delivery specifications is obtained. At the beginning of the ABD step 4, the D knows exactly what components should be avoided for their current design. Comparatively, in CDP, this information is only known later, after step 7. A delay in acquiring this strategic information directly increases the risk of creating designs affected by unavailability, and thus unacceptable. Such a situation forces the D to iterate a new time into the entire design process (and, also, feedback loops) closely to TtoM. It significantly increases the time required to produce a successful design (i.e., an available DO) by generating multiple unavailable DI.

The examination of the ABD methodology shows that fewer steps (11 steps instead of 13) and fewer feedback loops (2 instead of 9) are needed compared to CDP.

6. Design Case Study of a Ball Screw Drive Actuator (BSD)

6.1. Sub-Assembly, Families and Components

To compare the effectiveness of the CDP and the ABD, an industrial case study of a ball screw drive actuator (BSD), as depicted in Figure 4, has been conducted. This BSD actuator can be considered an SB of an overall machine composed of several SB. Any SB is composed of a given set of standard components performing one or more given functions. The number of resulting families of components (i.e., components of the SB that accomplish an identical subset of functions required in the SB) is denoted n_F in the remainder of the paper. In the BSD case study, seven different families of standard components are considered to achieve the concept, accomplishing the following functions:

1. pair spindle/nut (it should be noted that the pair spindle and nut are non-dissociable components, fixed by their main geometrical properties: nominal diameter and pitch, following the DIN 69051-2 [62] or ISO 3408-2 [63] standards)
2. pillow block
3. preloading nut
4. rod’s end
5. coupling
6. motor
7. safety brake

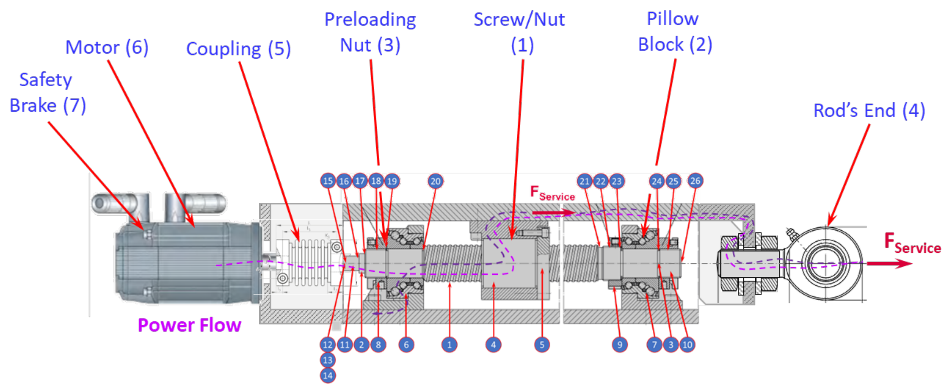

Figure 4. BSD case study (in this design, 7 families of standard components are considered).

Note that additional functions may require additional families. If so, these additional requirements should have been depicted within the specifications.

Where the CDP only proceeds sequentially by selecting one component from each family (in the BSD case study, 1 SB containing seven components, each from a different family), the ABD proceeds otherwise: a number of component candidates (denoted n_{CpF}) for each family are retained during the ABD step 3. For each family composing the design concept, an arbitrary number n_{CpF} of components is selected. Note that, in practice, the number of components per family n_{CpF} may vary from one family to another. However, for clarity, we will assume an identical number of components across all the identified families of a given concept in the remainder of the paper.

Therefore, for each of the CDP's TC per component, ABD will have to proceed n_{CpF} times this specific TC. In the current BSD case study, if we denote n_{TCpC} the number of TC per component (e.g., $n_{\text{TCpC}} = 10$ TC to be performed for each component), CDP would have to perform

$$n_{\text{F}} \cdot n_{\text{CpF}} \cdot n_{\text{TCpC}} = 7 \cdot 1 \cdot 10 = 70 \text{ TC} \tag{1}$$

Oppositely, in ABD, because each family is fed with a given number of candidate-components (e.g., $n_{\text{CpF}} = 5$), the number of technical checks to be performed will then be:

$$n_{\text{F}} \cdot n_{\text{CpF}} \cdot n_{\text{TCpC}} = 7 \cdot 5 \cdot 10 = 350 \text{ TC} \tag{2}$$

ABD Step 5 is thus far more time-consuming and calls logically for automation to reduce the DT.

Further, in the case where all selected components are available and technically satisfactory, CDP generates only one satisfactory DO in one DI. Under the same conditions, ABD generates more DO in a single DI. In ABD, the D will anyway have to make multiple TC over the larger amount of selected components (n_{CpF} gives $n_{\text{CpF}} \cdot n_{\text{TCpC}}$ TC to be performed). This will increase design time (DT). In this case and under specific working conditions (1 design option, full availability), CDP would be more efficient. Such a situation is highly unlikely in ABD: at full availability of all components of a given concept, the only reason to perform multiple DI would be to technically compare multiple DO, e.g., to optimize the design. Otherwise, $n_{\text{CpF}} = 1$ and the step of the availability check would not exist. Such are the hypotheses under which the CDP is usually performed.

However, in the current industrial practice, components may be unavailable at the required time. This forces designers to perform multiple DI (their number is denoted n_{DI}) to achieve a timely available DO. If the CDP is performed twice, the D has verified

$$n_{\text{DI}} \cdot n_{\text{F}} \cdot n_{\text{CpF}} \cdot n_{\text{TCpC}} = 2 \cdot 7 \cdot 1 \cdot 10 = 140 \text{ TC} \tag{3}$$

For each iteration, the availability check may require restarting the DI, incrementing n_{DI}, and thereby strongly increasing the total number of TC.

Furthermore, the D usually does not have the availability information about standard components in real time, which often forces them to reiterate a certain number of times before finding an available DO.

Knowing the number of DI required to achieve one available DO would be very helpful. The number of DI to be performed before obtaining an available DO is dependent on the ratio of available components within a given family (availability ratio, δ_f). Therefore, it is crucial to evaluate the impact of the availability ratio δ_f on the number of DI, given the number of desired available DO (n_{DO}). A probability analysis can yield such an evaluation.

6.2. Probability of Being Successful While Designing with CDP: Availability Ratio δ

The number of DI (n_{DI}) that the designer must perform before getting an available design option (DO) depends on δ_f. The fewer components available (at the specified time), the more the designer will have to iterate and generate multiple design iterations (DI). In the following and by simplification, we will consider that the availability ratio is the same for all families of a given design, thus, $\delta_f = \delta, \forall f \in \{1 \ldots n_{\mathrm{F}}\}$.

Depending on δ, one should first determine the probability to select successfully satisfactory available components and to achieve a successful design. Then, it will be possible to evaluate the number of DI (n_{DI}) necessary to obtain a full set of available components that will give, at least, one available design, thus, one SO.

Dantinne conducted a detailed analysis of that question considering that the selection of a component within a given initial component's space corresponds to a probabilistic draw without replacement [64]. In this case, the D is assumed to have a given space of candidate components for the design and if one selected component is not satisfactory, the D will disregard it for following selections. In this context, the use of a hypergeometrical distribution (comparable results are achieved using a geometrical distribution) under the following hypotheses was made:

1. δ is the same for every family of components;
2. n_{CpF} is the same for every family;
3. each family is independent from the others.

In practice, δ may vary from one family to another, but the worst design situation occurs when drastic shortages (low δ values) exist on all the considered families. The influence of δ is studied at length, in particular in Section 8.3. The limit case of a shortage in only 1 family of components, while the others are fully available, was checked by simulation and yielded results similar to those presented in the remainder of the paper.

Likewise, the engineering practice shows that the D tends to increase n_{CpF}, which in turn increases the design time. Keeping n_{CpF} at a common value across families should allow keeping the design time within reasonable values. Further, without prior knowledge of the δ value for each family, setting n_{CpF} at a common value across the families is a sensible approach.

The independence of the family of components is the normal situation in industrial practice. Components with different functionalities are generally not produced on the same manufacturing lines. The families' availability is determined by their own ERP planning, thereby making them independent.

Expressing the probability of selecting components that will yield one available DO composed of n_{F} standard components is usually done with a given confidence level c (e.g., $c = 95\%$ or 99.9%). The probability of being successful is thus expressed by

$$\mathcal{P}(\mathrm{DO}) = c \tag{4}$$

$$\mathcal{P}(\mathrm{DO}) = \prod_{f=1}^{n_{\mathrm{F}}} \mathcal{P}(f) \tag{5}$$

where

- $\mathcal{P}(\mathrm{DO})$ is the probability of generating one available DO;
- c is the confidence level of obtaining one available DO, here $c = 0.95 = 95\%$;
- $\mathcal{P}(f)$ is the probability of drawing at least one available component within family f.

Under the working hypothesis of the BSD case study, that initial spaces of components are the same and given the availability ratio δ (i.e., $\mathcal{P}(f)$ is identical for all families), we can express the value of $\mathcal{P}(f)$ required to reach the confidence level c:

$$\mathcal{P}(f) = [\mathcal{P}(\mathrm{DO})]^{\left(\frac{1}{n_{\mathrm{F}}}\right)} = c^{\left(\frac{1}{n_{\mathrm{F}}}\right)} \quad (6)$$

In the case of the BSD case study, $n_{\mathrm{F}} = 7$, which yields $\mathcal{P}(f) = 0.95^{(1/7)} = 0.9927$.

Thus, for each family composing the concept, the probability of successfully drawing an available component within this family should be at least 99.27% to be sure with a confidence level of 95% that an available DO will be found.

Now knowing the required $\mathcal{P}(f)$ necessary to be successful, the number of necessary draws, without replacement, to be done within that family, can be found with the hypergeometric distribution. The hypergeometric distribution is defined as follows [65]: the variable X follows a hypergeometric distribution if it takes the value $q = 0, 1, \ldots, \min(n_{\mathrm{Draws}}, K)$ with the probability:

$$\mathcal{P}(X = q) = \frac{\binom{K}{q}\binom{n_{\mathrm{CpF}} - K}{n_{\mathrm{Dr}} - q}}{\binom{n_{\mathrm{CpF}}}{n_{\mathrm{Dr}}}} \quad (7)$$

where

- n_{Dr} is the number of components' draws to be done;
- q is the number of available components to be drawn (in this case, $q = 1$);
- K is the number of available components within the family ($K = \delta \cdot n_{\mathrm{CpF}}$).

In the BSD case study, the goal is to determine how many draws, n_{Dr}, without replacement, we would need per family to find at least one available component within that family. Because of the assumption that δ is the same for all families, n_{Dr} without replacement per family will thus be the same.

Knowing n_{Dr} allows estimating the number of DI that the D must perform in the CDP before they can assemble at least one available design. Given the probabilistic approach, the value is assumed to yield a 95% success rate. In the hypergeometric distribution, different values of n can yield the probability of having no available component in the draw. Its complement gives the probability of getting at least one available component within the draw.

Applied to the BSD case study ($n_{\mathrm{F}} = 7$), Dantinne was able to find the values summarized in Table 1. Dantinne also provided extensions of that table for larger numbers of families within the given design, and the results were validated by a Monte Carlo simulation approach [64].

As shown in Table 1, for an SB composed of seven families of components, having $\delta = 0.6$ (i.e., our BSD case study), $n_{\mathrm{Dr}} = 5$. If δ increases, more parts are available: achieving an available DO requires fewer draws and, thus, fewer DI. Obviously, when all components are available ($\delta = 1$), only one draw per family is sufficient to yield an available DO. On the other hand, in the case of shortages, fewer parts are available, and the number of draws required to achieve an available DO increases (e.g., up to 18 for an availability ratio of $\delta = 0.1$).

Table 1. n_{Dr} to be done for given values of n_F and δ.

n_F	Availability Ratio (δ)								
	0.1	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**
1	16	10	7	6	4	3	3	2	2
3	17	12	9	7	5	4	4	3	2
5	18	13	10	7	6	5	4	3	2
7	18	13	10	8	6	5	4	3	2
9	18	14	10	8	6	5	4	3	2
11	19	14	10	8	6	5	4	3	2
13	19	14	11	8	7	5	4	3	3
15	19	14	11	9	7	6	4	4	3
17	19	14	11	9	7	6	4	4	3
19	19	14	11	9	7	6	4	4	3

Another conclusion of this evaluation is that the number of draws to be made does not vary very strongly with the number of families considered. Between $n_F = 1$ and $n_F = 19$, the average variation of the number of draws to be made is 53.26%. If a larger number of families is considered as a baseline, the variation is reduced: between $n_F = 7$ and $n_F = 19$, this variation falls to 15.57%.

However, not all available DI are technically satisfactory. If not, additional component draws are required, further increasing the treatment time. The probabilistic analysis confirms the need to consider only the available components, while retaining multiple components per family to increase design success. Such an adapted methodology is, precisely, the one pursued in ABD.

7. Timeline Models for Both Design Processes

Allocating time intervals to each step of both design processes, as depicted in Figure 3, allows assessing the TPT and the DT required to generate n_{DO} available DO and comparing the performance of both design processes (CDP and ABD). A description of the actions included in each step of the CDP, as well as their starting point, actors, ending point, and deliverables, is provided in Table 2. The durations of each step are quantified in Table 3, based on ETO industrial practice [61]. Likewise, Tables 4 and 5 provide respectively qualitative and quantitative descriptions of the steps of ABD.

For both the CDP and ABD, numerous feedback loops, presented in Figure 3, may require several iterations. However, to enhance the clarity of the presentation, Tables 2 and 4 present the positive outcome deliverables. The variability of the number of loops necessary to accomplish a project is reflected in the wide range provided as order of magnitude of durations in Tables 3 and 5. The order of magnitude presented in the rightmost column of Tables 3 and 5 corresponds to the minimal and maximal observed values over actual industrial projects of various complexity, while keeping $n_{DO} = 1$. Average values for projects of the complexity of the reference case study of the BSD are presented in Section 8 .

Table 2. Qualitative description of the steps of the CDP.

Step	Name	Starting Point	Actor	Positive Outcome Deliverable
1	Specifications	Expression of the need	D, PM	Formatted, understandable and quantified commonly agreed specifications
2	Concept	Formatted specifications	D, PM	A concept that meets the specifications
3	Design	A concept that meets the specifications	D	n_{DO} materialized concepts
4.1	TC	Materialized concept—components	D	A set of results over different components' properties to be checked for their global properties
4.2	KDI	Materialized concept—SB	D	A set of results over different assembly properties required to gauge assembly
5	Synthesis	Results of TC	D, PM	Agreement of the PM to establish the BOM
6	BOM	Conclusions of the synthesis discussion	D	BOM and documentation
7	Availability check	BOM established at step 6	D, Associated services (AS, such as customer service, logistic or sales team)	Confirmation of the availability of components
8	Offering	Prices, Minimum order quantity (MOQ, which denotes the minimal number of components that a supplier will accept in an order), and delivery time for all components considered at step 7	D, AS	An official quote stating prices, delivery times, MOQ, delivery conditions and payment terms
9	Evaluation	Quote sent to PM at step 8	PM, AS	A list of pain points and/or questions regarding the proposed BOM
10	Negociation	Evaluation and review of quotes made at step 9	D, PM, AS	GO—NOGO to Step 11
11	Ordering	Negociated or reviewed quotes negociated at step 10	PM, AS	Official order
12	Delivery	Official order reviewed at step 11	D, AS	Components' delivery confirmation

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Table 3. Quantitative description of the CDP steps [61].

Step	Name	Actions	Duration	Order of Magnitude ($n_{DO} = 1$)
1	Specifications	• Need is described and clarified • Working perimeter is defined • Features are discussed and quantified	Δt_{Sp}	1 day to 1 week
2	Concept	• Specifications are finely analyzed, • Primary and secondary functions are defined, • State of the art is established, • One concept is drawn up, a kinematic scheme and/or sketches are created • n_F families of components are identified	Δt_{Conc}	1 day to 3 weeks
3	Design	For each DO: • Selection criteria are fixed Duration: Δt_{Crit} • 1 component is selected in each of the n_F families Duration: $\sum_{f=1}^{n_F} \Delta t_{Select}(f)$	$\Delta t_{Des}^{CDP} = \Delta t_{Crit} + \sum_{u=1}^{n_{DO}} \sum_{f=1}^{n_F} \Delta t_{Select}(f)$	1 day to 1 week
4.1	TC	For each DO: • Components are checked for their n_{TCpC} local properties	$\Delta t_{TC}^{CDP} = \sum_{u=1}^{n_{DO}} \sum_{f=1}^{n_F} \sum_{j=1}^{n_{TCpC}} \Delta t_{TC}(f, j)$	1 day to 1 week
4.2	KDI	• n_{KDI} KDI are selected Duration: $\Delta t_{Select\ KDI}$ Then, for each DO candidate: • Assembly's KDI are checked Duration: $\sum_{s=1}^{n_{KDI}} \Delta t_{KDI}(s)$	$\Delta t_{KDI}^{CDP} = \Delta t_{Select\ KDI} + \sum_{u=1}^{n_{DO}} \sum_{s=1}^{n_{KDI}} \Delta t_{KDI}(s)$	0.5 to 1 day
5	Synthesis	• Results of the technical checks are summarized in a concise way • Results are presented to Project Manager • Results are discussed with the Project Manager	$\Delta t_{Syn}^{CDP} = \sum_{u=1}^{n_{DO}} \Delta t_{Syn}$	1 day to 1 week

Table 3. *Cont.*

Step	Name	Actions	Duration	Order of Magnitude ($n_{DO} = 1$)
6	BOM	• List the retained components by their formal names and references • Document the retained sub-assemblies for further treatment	$\Delta t_{BOM}^{CDP} = \sum_{u=1}^{n_{DO}} \Delta t_{BOM}$	1 day to 1 week
7	Availability check	• Each retained component is checked for its availability within the specification time limit (Delay and MOQ) (n components)	$\Delta t_{Av}^{CDP} = \sum_{u=1}^{n_{DO}} \sum_{f=1}^{n_F} \Delta t_{Av}(f)$	1 day to 2 weeks
8	Offering	• A formal offer is established for each of the selected components (n Components)	$\Delta t_{Offer}^{CDP} = \sum_{u=1}^{n_{DO}} \sum_{f=1}^{n_F} \Delta t_{Offer}(f)$	1 day to 3 weeks
9	Evaluation	• Formal offers are analyzed • Prices and delivery times are examined • Delivery and payment terms are checked	Δt_{Eval}	1 week to 4 weeks
10	Negociation	• Review Step 9 pain points list • Solve potential issues directly • Disregard further step(s)	Δt_{Nego}	1 week to 3 weeks
11	Ordering	• Formalize the BOM ordering (sales and delivery terms) • Acquiring validation and authorized signature(s) from hierarchy • Transmit official order	Δt_{Order}	1 day to 3 weeks
12	Delivery	• Receive official order • Check adequacy of offer with order and accounting data • Execute official order • Confirm deliveries	Δt_{Deliv}	1 week to 52 weeks
		Total:	$\Delta t_{TPT}^{CDP}(n_{DO} = 1)$	22 days to 75 weeks

In evaluating the durations in the CDP, the following hypotheses are made:

- Only 1 concept is considered (a generalization could consider multiple concepts. To allow adequate comparison, the concepts should be the same in the CDP and ABD. In practice, experienced designers naturally change the concept when they cannot find satisfactory solutions to their design problem);
- The n_{DO} DO are generated sequentially;
- The DO are independent;
- n_{F} families of 1 component are considered per design option (DO);
- There is one number of components per family, $n_{\text{CpF}} = 1$;
- n_{TCpC} per component are to be computed;
- n_{KDI} KDIs must be checked for each design option (DO);
- $\Delta t_{\text{Deliv}} = \max_f \Delta t_{\text{Deliv}}(f)$, with $f \in \{1 \ldots n_{\text{F}}\}$, i.e., the DO delivery time is the maximum of the delivery times of each of the DO components.

The TPT needed for achieving n_{DO} independent DO may be expressed as

$$\begin{aligned}\Delta t_{\text{TPT}}^{\text{CDP}}(n_{\text{DO}}) = {} & \Delta t_{\text{Sp}} + \Delta t_{\text{Conc}} + \left(\Delta t_{\text{Crit}} + \sum_{u=1}^{n_{\text{DO}}} \sum_{f=1}^{n_{\text{F}}} \Delta t_{\text{Select}}(f)\right) + \left(\sum_{u=1}^{n_{\text{DO}}} \sum_{f=1}^{n_{\text{F}}} \sum_{j=1}^{n_{\text{TCpC}}} \Delta t_{\text{TC}}(f,j)\right) \\ & + \left(\Delta t_{\text{Select KDI}} + \sum_{u=1}^{n_{\text{DO}}} \sum_{s=1}^{n_{\text{KDI}}} \Delta t_{\text{KDI}}(s)\right) + \left(\sum_{u=1}^{n_{\text{DO}}} \Delta t_{\text{Syn}}\right) + \left(\sum_{u=1}^{n_{\text{DO}}} \Delta t_{\text{BOM}}\right) \\ & + \left(\sum_{u=1}^{n_{\text{DO}}} \sum_{f=1}^{n_{\text{F}}} \Delta t_{\text{Av}}(f)\right) + \left(\sum_{u=1}^{n_{\text{DO}}} \sum_{f=1}^{n_{\text{F}}} \Delta t_{\text{Offer}}(f)\right) + \Delta t_{\text{Eval}} + \Delta t_{\text{Nego}} + \Delta t_{\text{Order}} + \Delta t_{\text{Deliv}} \quad (8)\end{aligned}$$

In evaluating the durations in ABD, the additional hypotheses are made:

- Only n_{DO} DO are selected
- The selected KDI are checked only for the selected DO

In the case of ABD, the TPT needed to achieve n_{DO} independent DO may be expressed as

$$\begin{aligned}\Delta t_{\text{TPT}}^{\text{ABD}}(n_{\text{DO}}) = {} & \Delta t_{\text{Sp}} + \Delta t_{\text{Conc}} + \left(\Delta t_{\text{Crit}} + \sum_{f=1}^{n_{\text{F}}} \sum_{i=1}^{n_{\text{CpF}}} \Delta t_{\text{Select}}(f)\right) + \left(\sum_{f=1}^{n_{\text{F}}} \sum_{i=1}^{n_{\text{CpF}}} \Delta t_{\text{Av}}(f)\right) \\ & + \left(\delta \sum_{f=1}^{n_{\text{F}}} \sum_{i=1}^{n_{\text{CpF}}} \sum_{j=1}^{n_{\text{TCpC}}} \Delta t_{\text{TC}}(f,j)\right) + \left(\sum_{u=1}^{n_{\text{DO}}} \Delta t_{\text{Pre-Select}}\right) + \left(\Delta t_{\text{Select KDI}} + \sum_{u=1}^{n_{\text{DO}}} \sum_{s=1}^{n_{\text{KDI}}} \Delta t_{\text{KDI}}(s)\right) \\ & + \left(\sum_{u=1}^{n_{\text{DO}}} \Delta t_{\text{Syn}}\right) + \left(\sum_{u=1}^{n_{\text{DO}}} \Delta t_{\text{BOM}}\right) + \left(\sum_{u=1}^{n_{\text{DO}}} \sum_{f=1}^{n_{\text{F}}} \Delta t_{\text{Offer}}(f)\right) + \Delta t_{\text{Order}} + \Delta t_{\text{Deliv}} \quad (9)\end{aligned}$$

Table 4. Qualitative description of the steps of ABD.

Step	Name	Starting Point	Actor	Positive Outcome Deliverable
ABD1	Specifications	Expression of the need	D, PM	Formatted, understandable and quantified commonly agreed specifications
ABD2	Concept	Formatted specifications	D, PM	A concept that meets the specifications
ABD3	Design	A concept that meets the specifications	D	n_F families, each including n_{CpF} components identified, meeting the concept defined at step ABD2
ABD4	Availability check	A table of components candidates for each family identified at step ABD2	D, AS	A table of available components for each family
ABD5	TC	A table of available components sorted by availability at step ABD4	D	A table of available components that individually fulfill the TC
ABD6	Preselection of SB	A table of available components that meet the TC evaluated at step ABD5	D *	A list of available designs that fulfill the TC, sorted by a characteristic value denoting the combination of safety ratios of components included in the design
ABD7	KDI	A sorted table of available, TC-validated DO candidates obtained at ABD6	D *	A list of available DO, sorted by KDI
ABD8	Synthesis	A table of available DO ordered by their KDI evaluated at step ABD7	D, PM *	An agreement toward a DO of which the BOM is to be established
9	BOM	All DO retained at step ABD8	D *	A BOM and its documentation
10	Offering	BOM obtained at step 9	D, AS *	An official quote stating prices, delivery times, MOQ, delivery conditions and payment terms
11	Ordering	Offer made at step 10	PM, AS	Official order
12	Delivery	Official order reviewed at step 11	D, AS	Components' delivery confirmation

An asterisk denotes that the step can be partially or fully automated, potentially requiring no actor.

Table 5. Quantitative description of ABD steps [61].

Step	Name	Actions	Duration	Order of Magnitude ($n_{\mathrm{DO}} = 1$)
ABD1	Specifications	• Need is described and clarified • Working perimeter is defined • Features are discussed and quantified	Δt_{Sp}	1 day to 1 week
ABD2	Concept	• Specifications are finely analyzed, • Primary and secondary functions are defined, • State of the art is established, • One concept is drawn up, a kinematic scheme and/or sketches are created • n_{F} families of components are identified	Δt_{Conc}	1 day to 3 weeks
ABD3	Design	For each family of components: • Selection criteria are fixed • n_{CpF} components are selected in each of the n_{F} families Duration: $\sum_{f=1}^{n_{\mathrm{F}}} \sum_{i=1}^{n_{\mathrm{CpF}}} \Delta t_{\mathrm{Select}}(f)$	$\Delta t_{\mathrm{Des}}^{\mathrm{ABD}} = \Delta t_{\mathrm{Crit}} + \sum_{f=1}^{n_{\mathrm{F}}} \sum_{i=1}^{n_{\mathrm{CpF}}} \Delta t_{\mathrm{Select}}(f)$	1 day to 1 week
ABD4	Availability check	• All retained components are checked for their availability within the specification time limits and MOQ	$\Delta t_{\mathrm{Av}}^{\mathrm{ABD}} = \sum_{f=1}^{n_{\mathrm{F}}} \sum_{i=1}^{n_{\mathrm{CpF}}} \Delta t_{\mathrm{Av}}(f)$	1 day to 2 weeks
ABD5	TC and safety ratio (s)	• For all available components within each family: computing for each TC a safety ratio $s_j = \frac{p_j}{p_{ref}}$, with p_j the component's property being checked and p_{ref} the criterion value being checked by the TC • All components for which $s_j < s_{limit}$ are withdrawn from consideration, with s_{limit} the threshold for component acceptability	$\Delta t_{\mathrm{TC}}^{\mathrm{ABD}} = \delta \sum_{f=1}^{n_{\mathrm{F}}} \sum_{i=1}^{n_{\mathrm{CpF}}} \sum_{j=1}^{n_{\mathrm{TCpC}}} \Delta t_{\mathrm{TC}}(f, j)$	1 day to 1 week

Table 5. *Cont.*

Step	Name	Actions	Duration	Order of Magnitude ($n_{DO} = 1$)
ABD6	Preselection of SB	• For all remaining components, the generalized safety ratio $\pi_i = \prod_{j=1}^{n_{TCpC}} s_j$ is computed • In each family, the table of components is sorted by π_i, and combinations of components with the best π_i are generated automatically	$\Delta t^{ABD}_{Pre\text{-}Select} = \sum_{u=1}^{n_{DO}} \Delta t_{Pre\text{-}Select}$	A few minutes to a few hours *
ABD7	KDI	• n_{KDI} KDI are selected, then computed for each DO candidate • The list of DO is sorted by KDI value	$\Delta t^{ABD}_{KDI} = \Delta t_{Select\ KDI} + \sum_{u=1}^{n_{DO}} \sum_{s=1}^{n_{KDI}} \Delta t_{KDI}(s)$	A few hours *
ABD8	Synthesis	• The results of the TC and KDI are summarized in a concise way • The results are presented and discussed with the PM	$\Delta t^{ABD}_{Syn} = \sum_{u=1}^{n_{DO}} \Delta t_{Syn}$	A few hours to a few days
9	BOM	• A list of DO with their components is created, with appropriate documentation on the retained DO	$\Delta t^{ABD}_{BOM} = \sum_{u=1}^{n_{DO}} \Delta t_{BOM}$	A few hours to a few days *
10	Offering	• A formal offer is established for all selected components	$\Delta t^{ABD}_{Offer} = \sum_{u=1}^{n_{DO}} \sum_{f=1}^{n_F} \Delta t_{Offer}(f)$	A few hours to a few days *
11	Ordering	• Formalize the BOM ordering (sales and delivery terms) • Acquiring validation and authorized signature(s) from hierarchy • Transmit official order	Δt_{Order}	1 day to 3 weeks
12	Delivery	• Receive official order • Check adequacy of offer with order and accounting data • Execute official order • Confirm deliveries	Δt_{Deliv}	1 week to 52 weeks
		Total:	$\Delta t^{ABD}_{TPT}(n_{DO} = 1)$	3 to 64 weeks

An asterisk denotes that the step can be fully automated, reducing its duration to a few minutes at most.

To be successful, a design method's TPT, expressed in (8) and (9) for the CDP and ABD, respectively, should not exceed the TtoM. From these equations, the durations on which the D has a null or marginal influence (including evaluation, negotiation, ordering, etc.) can be removed, which leads to the expression of the DT for both the CDP and ABD in (10) and (11):

$$\Delta t_{\mathrm{DT}}^{\mathrm{CDP}}(n_{\mathrm{DO}}) = \Delta t_{\mathrm{Sp}} + \Delta t_{\mathrm{Conc}} + \left(\Delta t_{\mathrm{Crit}} + \sum_{u=1}^{n_{\mathrm{DO}}} \sum_{f=1}^{n_{\mathrm{F}}} \Delta t_{\mathrm{Select}}(f)\right) + \left(\sum_{u=1}^{n_{\mathrm{DO}}} \sum_{f=1}^{n_{\mathrm{F}}} \sum_{j=1}^{n_{\mathrm{TCpC}}} \Delta t_{\mathrm{TC}}(f,j)\right) + \left(\Delta t_{\mathrm{Select\ KDI}} + \sum_{u=1}^{n_{\mathrm{DO}}} \sum_{s=1}^{n_{\mathrm{KDI}}} \Delta t_{\mathrm{KDI}}(s)\right) + \left(\sum_{u=1}^{n_{\mathrm{DO}}} \Delta t_{\mathrm{Syn}}\right) + \left(\sum_{u=1}^{n_{\mathrm{DO}}} \Delta t_{\mathrm{BOM}}\right) + \left(\sum_{u=1}^{n_{\mathrm{DO}}} \sum_{f=1}^{n_{\mathrm{F}}} \Delta t_{\mathrm{Av}}(f)\right) + \left(\sum_{u=1}^{n_{\mathrm{DO}}} \sum_{f=1}^{n_{\mathrm{F}}} \Delta t_{\mathrm{Offer}}(f)\right) \quad (10)$$

$$\Delta t_{\mathrm{DT}}^{\mathrm{ABD}}(n_{\mathrm{DO}}) = \Delta t_{\mathrm{Sp}} + \Delta t_{\mathrm{Conc}} + \left(\Delta t_{\mathrm{Crit}} + \sum_{f=1}^{n_{\mathrm{F}}} \sum_{i=1}^{n_{\mathrm{CpF}}} \Delta t_{\mathrm{Select}}(f)\right) + \left(\sum_{f=1}^{n_{\mathrm{F}}} \sum_{i=1}^{n_{\mathrm{CpF}}} \Delta t_{\mathrm{Av}}(f)\right) + \left(\delta \sum_{f=1}^{n_{\mathrm{F}}} \sum_{i=1}^{n_{\mathrm{CpF}}} \sum_{j=1}^{n_{\mathrm{TCpC}}} \Delta t_{\mathrm{TC}}(f,j)\right) + \left(\sum_{u=1}^{n_{\mathrm{DO}}} \Delta t_{\mathrm{Pre\text{-}Select}}\right) + \left(\Delta t_{\mathrm{Select\ KDI}} + \sum_{u=1}^{n_{\mathrm{DO}}} \sum_{s=1}^{n_{\mathrm{KDI}}} \Delta t_{\mathrm{KDI}}(s)\right) + \left(\sum_{u=1}^{n_{\mathrm{DO}}} \Delta t_{\mathrm{Syn}}\right) + \left(\sum_{u=1}^{n_{\mathrm{DO}}} \Delta t_{\mathrm{BOM}}\right) \quad (11)$$

8. Quantitative Comparison of Both Design Processes

Quantitative comparisons of CDP and ABD were performed using an industrial case study of a BSD, which materializes the seven functions described in Figure 4. The industrial practice expresses commonly project times in calendar or working weeks (1 calendar week = 40 engineering hours, 1 year = 52 calendar weeks): this time framework is used in the remainder of the paper.

In the context of this case study, the required realistic parameters are identified in Table 6. For each component, 16 TC were performed (e.g., minimum static safety ratio, limiting speed, reference rating life, maximum working temperature, deformation under load, etc.) and 3 KDI (overall axial space used, price, and margin) were computed for sorting the first 3 best available DO.

Table 6. Parameters of the BSD study, based on similar industrial ETO projects [61].

Parameter	Value
n_{CpF}	5
δ	0.6
n_{TCpC}	16
n_{KDI}	3

The data collected for this real-world case study are presented in Table 7. It presents average values observed for projects of similar complexity to the reference BSD case study. In this table, a distinction is made between variations that occur in the industrial practice, i.e.,

1. Manual design is performed without the assistance of a computer-aided system. Printed or online technical catalogs are consulted to pre-select standard components, and straightforward design-documented calculations (by hand or with low-tech tools) are performed. After technical checks (TC) and global properties are performed, the synthesis and the BOM are established manually and transferred to other teams ("over the wall" approach) for checking BOM availability. This is usually realized from requests for quotation done by the purchase department to different suppliers. Offers are received, examined, and summarized to identify the best delivery times of BOM components. All this process is realized manually, which takes time. This method of design concerns specifically engineering offices (e.g., assemblers) that are treating non-recurrent machine designs. It may also concern completely new designs where engineering design, overall TC to be performed, and their orders of magnitude are not mastered enough. In these cases, the D wants to understand more accurately the relevant influencing parameters, and feels the need to explore the overall calculation protocol. These engineering offices generate individual designs after having performed the necessary TC manually. For completely new designs, R&D purposes, prototypes, or critical applications (e.g., where the 4-eyes principle is required), manual design is usually the way projects are managed in engineering to order design offices.
2. Semi-automated design is performed when the D deals with projects of similar complexities. The D may be used to work with identical groups of standard components [66]. In such situations, the performed TC are well known, orders of magnitude better mastered, and calculations can be more or less automated (e.g., systematic (re)design of similar or same products for different application purposes). Application engineering treating variation designs may also have developed some engineering tools for partially automatizing some of the systematically identified TC of components. The nature, number of TC and verification flowchart are known, mastered, and regularly practiced. The TC are listed and (self)programmed (e.g., in Excel, MatLab, MathCad, etc.) to generate quickly given formatted results (e.g., minimum static safety factor, nominal rating life, power rating used, etc.). Some of these routines are also offered by component manufacturers (e.g., Medias Professional by Schaeffler), while others can be programmed directly by engineering offices themselves. Most of the time, these routines concern only one standard component at a time. They do not allow any integration of different sets of standard components. Sometimes, this forces the D to perform KDI calculations separately or manually. However, they allow quicker verifications of given standard components, which induces non-negligible quick wins on the DT. It should be noted that no automatization of availability checks is considered in the semi-automated approach.
3. Automated design is allowed thanks to integrated tools that some manufacturers developed (e.g., BearinX by Schaeffler [67], KISSsoft by KISSLING AG & Co. KG [68], etc.). These tools can combine diverse types of machine components (e.g., shaft, bearings, pulleys, etc.). They include large components libraries enabling designers to assemble different machine elements together into given SB. The design being virtually created, these software solve TC and KDI calculations together over a whole SB. Detailed and synthetic results are generated and available under the form of printable calculation notes or numerical files. These files can be quickly reused for further automatization or optimization. In most cases, these tools are private internal software used by application engineering of standard components manufacturers. They allow definition, assembly, static and kinematic liaison between objects, load cases introduction and simulations of given components assemblies working under

given conditions. Under licenses, major customers (e.g., serial machine manufacturers) may have access to partial or full versions of these software. They reduce drastically the amount of work necessary from engineering offices to perform design scenarios. The DT and product launches are drastically shortened and/or quick generation of multiple DO allow easy optimization of products, fast redesign, or easy concurrent engineering. Additionally, parallel to the automation of TC, manufacturers also have access to the instantaneous availability information in general (e.g., stocks levels, planning, production batches, order entries, production issues, etc.) or in part (e.g., limited to stock levels, agenda of stock entries, most used components, etc.). This real or discrete time information issued from enterprise resource planning (ERP) platforms can also be directly consulted by designers or be linked with integrated design software (e.g., in the BearinX software).

Table 7. Average elementary durations of the steps in calendar weeks and usual units (hours or seconds) for the BSD case study in CDP (manual, semi-automated) and ABD (automated), based on measurements in similar ETO projects [61].

Duration	**Manual**		**Semi-Automated**		**Automated**	
Δt_{Sp}	0.37	(14.80 h)	0.37	(14.80 h)	0.37	(14.80 h)
Δt_{Conc}	0.37	(14.80 h)	0.37	(14.80 h)	0.37	(14.80 h)
Δt_{Des}^{CDP}	0.3975	(15.90 h)	0.3975	(15.90 h)	0.3975	(15.90 h)
Δt_{TC}	4.12	(164.80 h)	0.4480	(17.92 h)	0.000336	(48.38 s)
Δt_{KDI}	0.1410	(5.64 h)	0.0120	(0.48 h)	0.000003	(0.32 s)
Δt_{Av}	0.2555	(10.22 h)	0.2555	(10.22 h)	0.000035	(5.04 s)
Δt_{Syn}	0.29	(11.60 h)	0.29	(11.60 h)	0.000001	(0.14 s)
Δt_{BOM}	0.10	(4 h)	0.10	(4 h)	0.000001	(0.14 s)
Δt_{Offer}	0.1050	(4.20 h)	0.1050	(4.20 h)	0.000001	(0.14 s)
Δt_{Eval}	2.20	(88.00 h)	2.20	(88.00 h)	2.20	(88.00 h)
Δt_{Nego}	0.20	(8.00 h)	0.20	(8.00 h)	0.20	(8.00 h)
Δt_{Order}	0.20	(8.00 h)	0.20	(8.00 h)	0.20	(8.00 h)
Δt_{Deliv}	11	(440.00 h)	11	(440.00 h)	11	(440.00 h)

In common industrial practice, the D working in engineering offices does not have access to specific information such as prices and delivery times of components. They must obtain such information through specific requests to suppliers called request for quotation. Partially automated tasks concern only TC and, sometimes, KDI calculations, as shown in Table 8. As shown in this table, the CDP cannot be automated further than the semi-automation stage. Furthermore, the automation of the availability check is only possible if the D has instantaneous access to the availability data from the ERP systems, which is not currently the case in the CDP.

Table 8. Maximum automation potential for each design step, depending on the design process.

	Design Process	
	CDP	**ABD**
Specifications	×	×
Concept	×	×
Design	×	×
TC	✓	✓
KDI	✓	✓
Synthesis	×	✓
BOM	×	✓
Availability Check	×	✓

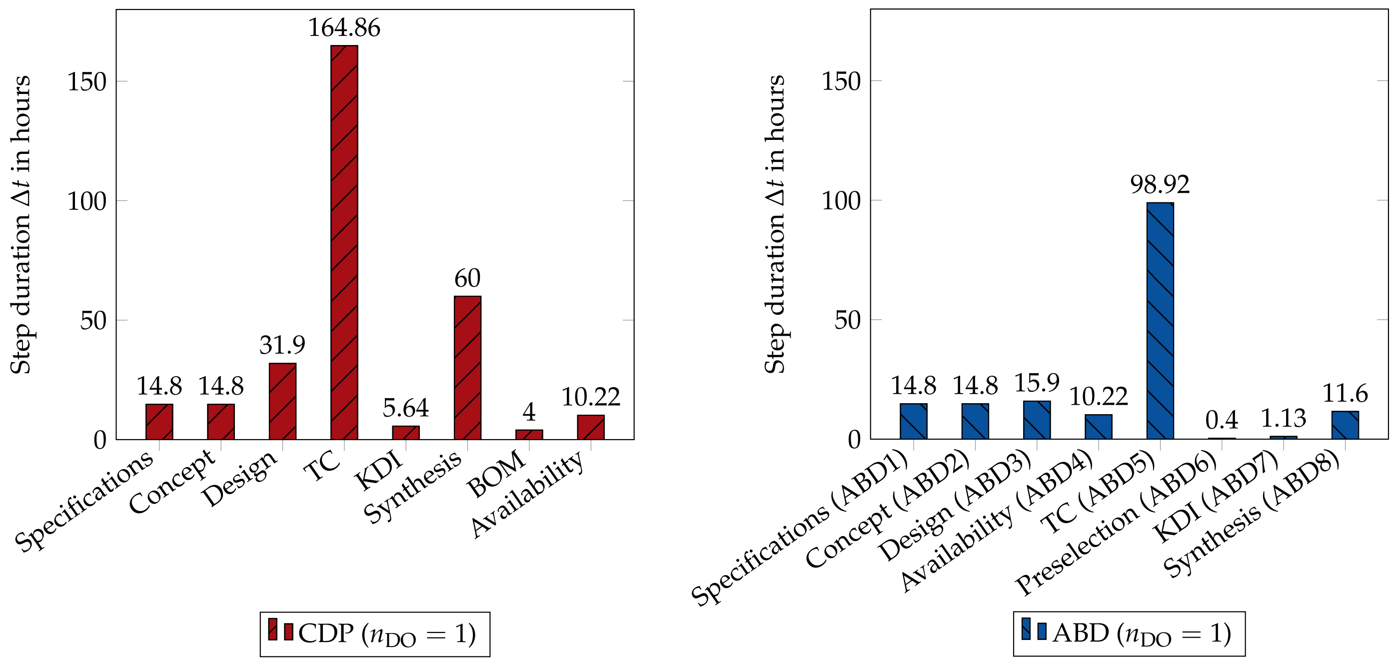
Only components manufacturers have access to delivery information and can advantageously use it within integrated design tools able to treat different machine components on the same engineering platform. Integrated engineering tools, such as BearinX, may directly take advantage of the ABD methodology. They effectively allow a full automatization (TC, KDI, availability, etc.) of important time-consuming design steps. They are also directly linkable with ERP platforms, making possible dynamic design routing, which can depend on market situation, production planning, or unplanned incidents.

8.1. Comparison of Step Durations

From Table 7, and using Equations (10) and (11), it is possible to compute each term of DT for both the CDP and ABD in the three relevant design modes: manual, semi-automated, and automated.

The DT for generating a single DO, at the availability ratio of $\delta = 0.6$, can be evaluated. For a manual design, the durations of the different steps composing the DT are shown, for the CDP and ABD, in Figure 5. These graphs show values that include the loops occurring in both processes, e.g., in case of insufficient availability of components that would require additional iterations. The required loops due to unavailability or unmet TC and KDI checks induce occasional loops back to Design in the CDP, which increases the overall duration of the Design step in that case. Figure 5b does not include a BOM step, as it is automatically included in ABD6, the components' references being already known at that stage.

Key values computed from these graphs are compared in Table 9. In this Table, the important DT gain of ABD over the CDP is shown, easing the D's tasks in the current economy. The method retains important proportions of added value actions for the D (in particular, the time proportion of TC and KDI checks is conserved), but significantly reduces the time proportion of less valuable actions, such as availability checks and syntheses.



(**a**) (**b**)

Figure 5. Distribution of time-consuming steps in (**a**) the CDP and (**b**) ABD approaches of the BSD case study, with identical parameters: $\delta = 0.6$, $n_{\mathrm{F}} = 7$, $n_{\mathrm{TCpC}} = 16$, $n_{\mathrm{KDI}} = 3$, in manual computation. In ABD (**b**), $n_{\mathrm{CpF}} = 5$.

Table 9. Comparison of key durations (in hours) in the CDP and ABD for the manual design of the BSD case study.

	CDP	Time Proportion of the CDP's DT	ABD	Time Proportion of ABD's DT	Gain of ABD over CDP
DT	306.22	100%	167.77	100%	45%
TC and KDI	170.51	56%	100.05	60%	41%
Availability, synthesis and BOM	74.22	24%	21.82	13%	71%

Moreover, automating time-consuming steps where possible (as noted in Table 5) would provide a decisive competitive advantage to the D by shortening the DT and, consequently, the TtoM.

8.2. Influence of Automation with Varying n_{DO}

The DT for both the CDP and ABD are compared in Figure 6 for the case of the BSD case study (manual design with $\delta = 0.6$): even if the number of DO is increased, ABD's DT remains always better than CDP's. Indeed, for $n_{DO} = 1$, ABD's DT is 45% shorter than CDP's. Further, the benefits of the ABD methodology increase with n_{DO}: with $n_{DO} = 3$, ABD's DT is 75% shorter than CDP's.

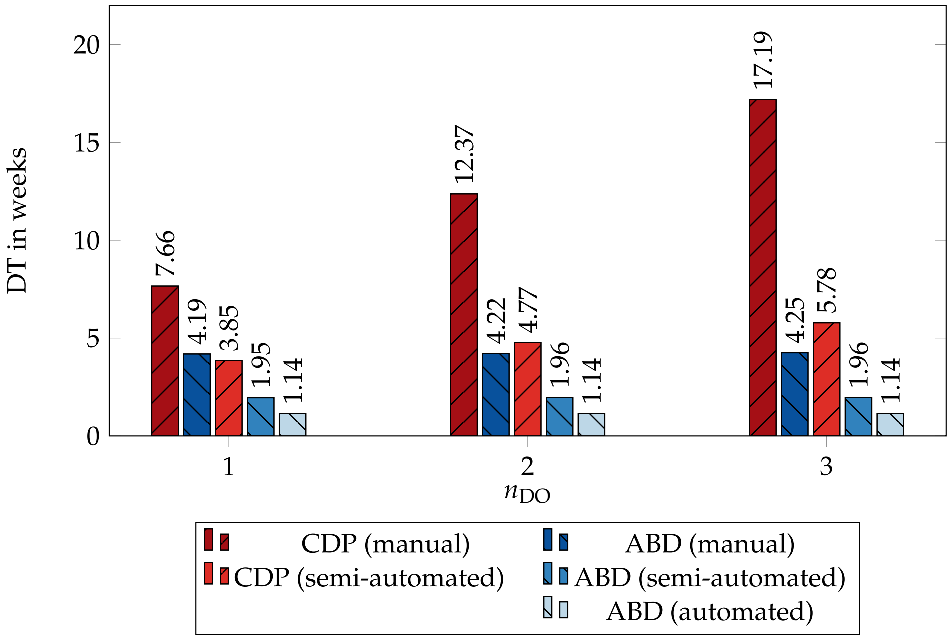


Figure 6. DT for both the CDP and ABD depending on n_{DO}, with $\delta = 0.6$, $n_F = 7$, $n_{TCpC} = 16$, and $n_{KDI} = 3$, in manual, semi-automated, and automated computations. In all ABD cases, $n_{CpF} = 5$.

In semi-automated design, only the TC and KDI are computed automatically. They can be automated both in the CDP and ABD. A first conclusion is that semi-automatization leads to a drastic reduction of DT. In Figure 6, comparing the manual and semi-automated design modes for CDP shows a reduction of DT of nearly a factor 2 for $n_{DO} = 1$. This reduction reaches a value of 2.97 for $n_{DO} = 3$ in CDP, showing again the drastic competitive advantage of automated design tasks. Further, semi-automating CDP allows reducing the DT to values more in line with current market constraints.

The semi-automation gain is even more important for ABD: a factor of 2.15 is achieved for $n_{\mathrm{DO}} = 1$ and a factor of 2.17 for $n_{\mathrm{DO}} = 3$, as shown in Figure 6. These results demonstrate the benefits of automating design tasks whenever possible, as it strongly shortens TtoM. It could also provide spare time for the D to refine the DO within the same time limit as in the manual mode.

Further, even if a semi-automation of design tasks is pursued for both design processes, ABD saves 49% of time in comparison with the CDP for $n_{\mathrm{DO}} = 1$ and 66% of time for $n_{\mathrm{DO}} = 3$.

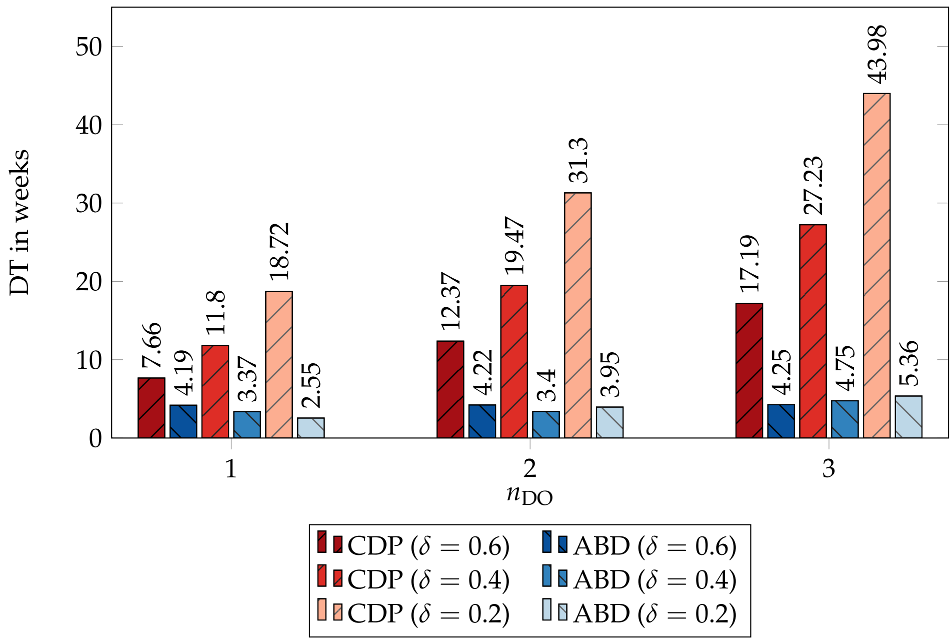
Additionally, automating further steps like availability check leads to further design time gains as shown in Figure 6. The automation of the availability check is only feasible when the availability data is made available to the D. This is the case with standard component manufacturers, which have that information and can link the ERP data to the D or their design tools. As soon as the TtoM is known (at the specification step), the D can automatically filter production plans and only allow selection of the components that are available at the specified TtoM. This can be done in several ways, e.g., by automatically bridging the ERP with the design tool, or by allowing the external D to access availability information through a web portal.

Having the availability information also allows automating other steps, such as Synthesis, BOM, and Offering. However, such full automation is not possible for the CDP. Therefore, DT improvements are only visible in ABD: for $n_{\mathrm{DO}} = 1$, the automated ABD saves 70% of time over the semi-automated CDP. This improvement factor reaches a value of 5.07 for $n_{\mathrm{DO}} = 3$, indicating a significant performance increase for ABD over the CDP. In the automated design mode, another conclusion can be drawn: achieving 1 or 3 design options requires an identical DT. This provides an additional competitive advantage for the D, as they can easily generate alternative designs. The possibility of generating multiple designs with no time cost opens up more discussion opportunities between the D and the PM. Furthermore, even if the DT is drastically reduced using ABD, incoming orders may impair component availability over the duration of the design; in such cases, alternate designs can circumvent this issue. Such a reserve of DO allows the D to avoid the undesirable issue of unavailable components at the TtoM.

8.3. Influence of the Availability Ratio

In practice, the availability ratio δ can vary from low values (shortage situation, $0.2 \leq \delta \leq 0.4$) to large ones (full availability, $\delta \geq 0.8$). The DT varies with δ, as shown in Figure 7, which corresponds to the BSD case study for $n_{\mathrm{DO}} \in \{1, 2, 3\}$ and, respectively, for $\delta \in \{0.2, 0.4, 0.6\}$. The Figure 7 shows the results both in manual and automated computation modes (semi-automated for CDP, due to full automation being impossible for CDP).

At low availability ($\delta = 0.2$), the number of DI to be made using CDP increases strongly as it was justified in the probabilistic analysis regarding the BSD case study. In this case, a correction must also be done in evaluating ABD's DT, because the starting n_{CpF} components selected in the ABD3 step may be insufficient. In this case, it is necessary to expand the initial design domain by increasing this number, or by introducing a loop between steps ABD3 and ABD4. For this reason, ABD's DT increases with n_{DO} more significantly at low δ values.



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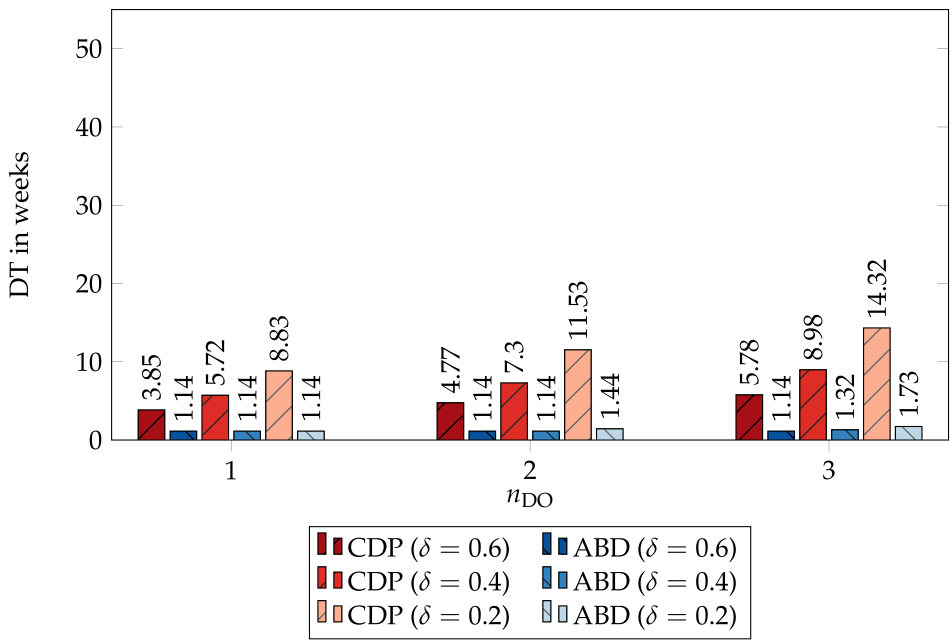


(**b**)

Figure 7. DT in (**a**) manual (ABD and CDP), and (**b**) automated computation (ABD) and semi-automated computation (CDP) depending on n_{DO}, for $\delta \in \{0.2, 0.4, 0.6\}$, with $n_F = 7$, $n_{TCpC} = 16$, $n_{KDI} = 3$. In all ABD cases, $n_{CpF} = 5$.

However, even in these circumstances, ABD's DT always remains largely below the CDP's, showing again ABD's benefits. Regardless, requiring a large n_{DO} at low δ values becomes unrealistic, because the number of DI necessary to find an available DO is too large. In such cases, the CDP design flow and logic are likely to be abandoned for the so-called "wild design" (opportunistic approach). For $n_{DO} = 1$, at low δ values, ABD's DT still diminishes, due to the availability check that limits drastically the components number: less components remain after ABD4, which induces less TC and KDI calculations to be performed, leading to a DT gain.

Likewise, for (semi-)automated design modes, even if the δ diminishes significantly, ABD's DT remains always shorter than CDP's. In shortage situations ($\delta = 0.2$), for $n_{\mathrm{DO}} = 1$, ABD's DT is 7.30 times shorter than CDP's. It reaches a factor of 8.27 for $n_{\mathrm{DO}} = 3$ at the same δ value. When δ increases, ABD's DT advantage is reduced, thanks to the increased probability of finding an available DO more quickly in CDP, but ABD's DT remains better nevertheless. Further, at hight δ values, ABD's DT shows less sensitivity to n_{DO}, as ABD's DT becomes dependent on fix duration design steps only, no loop between ABD3 and ABD4 being required. At medium availability values ($\delta = 0.6$), the DT saving factor between CDP and ABD remains above 3.38 for $n_{\mathrm{DO}} = 1$ and above 5.07 for $n_{\mathrm{DO}} = 3$.

Focusing the sensitivity analysis on δ allows finding the δ domain over which ABD's DT is always better than the CDP's. The corresponding curves are depicted in Figure 8 for the manual operations, for $n_{\mathrm{DO}} = 1$ and 3. The influence of δ in other calculation modes (semi- or fully automated) is shown in Appendix B.

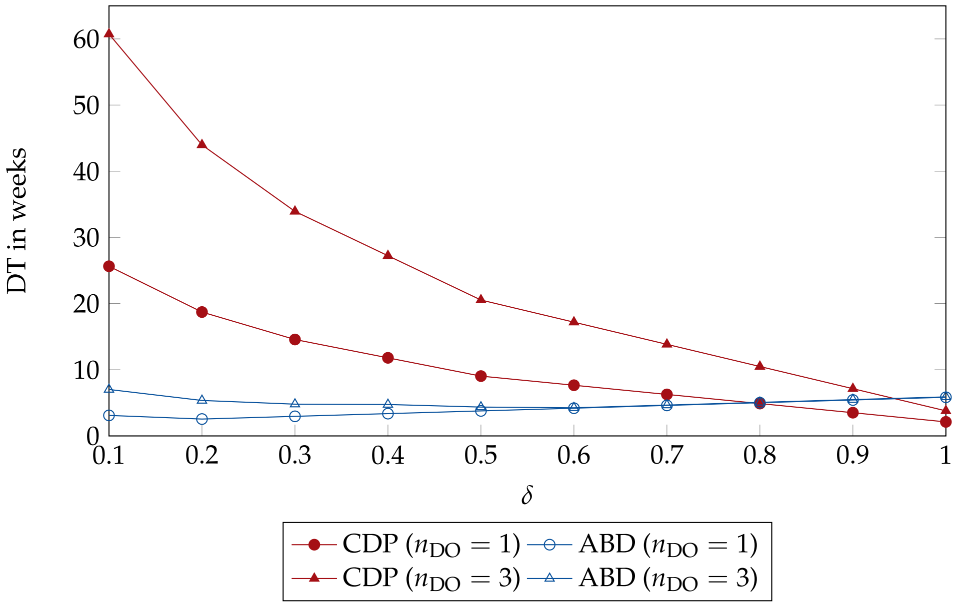


Figure 8. Variation of the CDP's (red, filled marks) and ABD's (blue, outline marks) DT with δ, for $n_{\mathrm{DO}} = 1$ (circle marks) and n_{DO} = 3 (triangle marks). In all cases, the calculations are manual, $n_{\mathrm{F}} = 7$, $n_{\mathrm{TCpC}} = 16$, $n_{\mathrm{KDI}} = 3$. In all ABD cases, n_{CpF} is corrected following (13).

As is shown in this graph, the CDP's DT diminish continuously as δ increases: the more available the components are, the smaller the number of DI needed will be to find one available DO, thus reducing the CDP's DT. On the contrary, at low δ values ($\delta \leq 0.3$), the initial number of components is not sufficient to find an available DO, leading to an additional DI. In ABD, the initial design space (i.e., n_{CpF}) may also be insufficient and may need to be enlarged depending on the number of desired DO. That is why, at low δ values, for ABD, a correction on n_{CpF} must be introduced. Denoting $\lceil x \rceil$ the least integer greater than or equal to x, an available DO is found if and only if the following condition is met for all families:

$$\lceil \delta \cdot n_{\mathrm{CpF}} \rceil \geq n_{\mathrm{DO}} \tag{12}$$

or

$$n_{\mathrm{CpF}} \geq \left\lceil \frac{n_{\mathrm{DO}}}{\delta} \right\rceil \tag{13}$$

Equation (13) allows determining the minimal n_{CpF} value required for a given δ to generate a given number of available DO (n_{DO}). This number is tabulated in Table 10. For low δ and large n_{DO} values, n_{CpF} should be increased to get enough successful draws of components, and in turn, the required number of available DO. Conversely, at high δ

values, it is not necessary to open the initial design space to be sure to find successful draws within it. While there is no assumption that the D has always prior knowledge of δ, an estimate of δ is necessary to update n_{CpF} according to (13). In that case, an estimate of δ can be made by referring to market statistics for the family of components, which offer a view of current shortages and trends. The designer can also contact manufacturers to obtain an estimate of δ.

Table 10. Necessary n_{CpF} at given δ values for to achieve the required n_{DO} available DO.

δ	n_{DO}				
	1	**2**	**3**	**4**	**5**
0.1	10	20	30	40	50
0.2	5	10	15	20	25
0.3	4	7	10	14	17
0.4	3	5	8	10	13
0.5	2	4	6	8	10
0.6	2	4	5	7	9
0.7	2	3	5	6	8
0.8	2	3	4	5	7
0.9	2	3	4	5	6
1	1	2	3	4	5

The corrected values obtained from (13) were used for drawing Figure 8. In this figure, for most $\delta \leq 0.8$, ABD remains better than CDP. In shortage situations ($\delta \leq 0.2$), the number of DI using the CDP is very large, which makes CDP inefficient. Even including the corrections on n_{CpF} for low δ values, ABD remains far quicker than the CDP (88% time reduction over the CDP for $\delta = 0.1$). However, when $\delta > 0.8$, the CDP's design time becomes shorter than ABD's: the components being available, an available DO can be found quickly (in a single DI if $\delta = 1$), and no correction on n_{CpF} is needed for ABD. Likewise, in the CDP, and with $\delta = 1$, a single DI is also sufficient to find an available DO. However, in that case, ABD's DT would be longer, because the D has to perform the TC and KDI checks on a larger number of components. In this situation, ABD generates several available DO that are not necessarily necessary.

In the same figure, similar curves are drawn in the case where $n_{\text{DO}} = 3$ is requested, in which case the crossing point of the curves is dispaced to $\delta > 0.9$. This is because ABD generates multiple available DO per DI, while the CDP requires at least one DI per DO.

Similar to the n_{CpF} correction at low δ values, reducing n_{CpF} at high δ values could be attempted if n_{CpF} is higher than the one found through (13). While this approach could reduce ABD's DT, it could lead to different issues: reducing to the strict minimum does not allow anymore the D to sort the DO by their KDI results. This is the reason why such a correction is not recommended at high δ values.

For the BSD case study, with $\delta = 0.6$, ABD takes 45% less time than the CDP to produce one available DO, and 75% less time than the CDP if $n_{\text{DO}} = 3$.

Finally, in full automation, even at full availability, ABD is always faster than the semi-automated CDP (which cannot be fully automated), as shown in Figure 9. By comparison with Figure 8, it shows that the full automation of ABD suppresses any δ threshold for DT gain, as ABD is then shorter than the CDP.

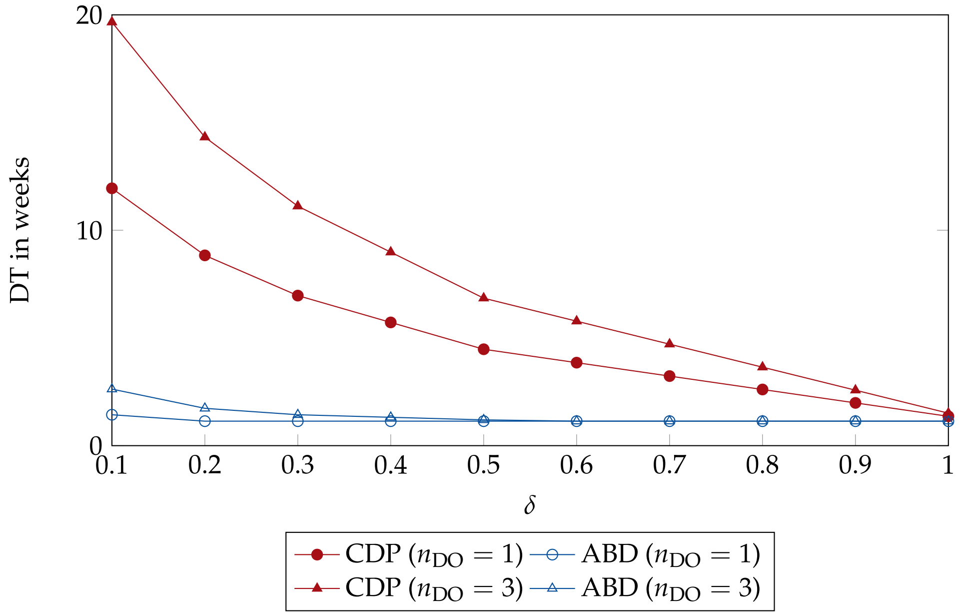


Figure 9. Variation of the CDP's (red, filled marks) and ABD's (blue, outline marks) DT with δ, for $n_{DO} = 1$ (circle marks) and n_{DO} = 3 (triangle marks). The CDP is semi-automated, while ABD is fully automated, $n_F = 7$, $n_{TCpC} = 16$, $n_{KDI} = 3$. In all ABD cases, n_{CpF} is corrected following (13).

A similar figure can be generated for the semi-automated design mode, as presented in Appendix B.

9. Sensitivity Analysis of ABD

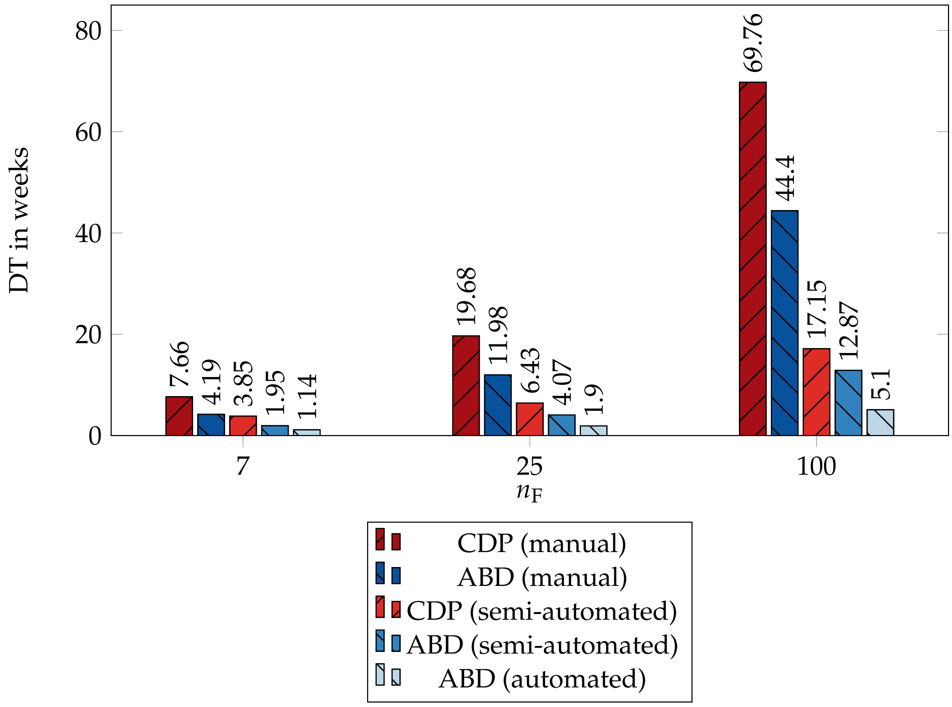
The CDP and ABD should both be sensitive to some extent to parameters, among which two stand out:

1. the number of families in the design (n_F)
2. the number of calculations to be made for assessing the components and designs (n_{TCpC} and n_{KDI}).

9.1. Number of Families n_F

To show the influence of these variables on the DT, a first sensitivity analysis was conducted on n_F, varying it from 7 to 100 (all other parameters being kept constant).

Figure 10 shows the CDP's and ABD's DT depending on n_F, keeping all other parameters constant. In manual design mode, even if the number of families increases from 7 to 100, the ABD methodology remains more efficient than the CDP. The gain that can be obtained under various conditions is summarized in Table 11.



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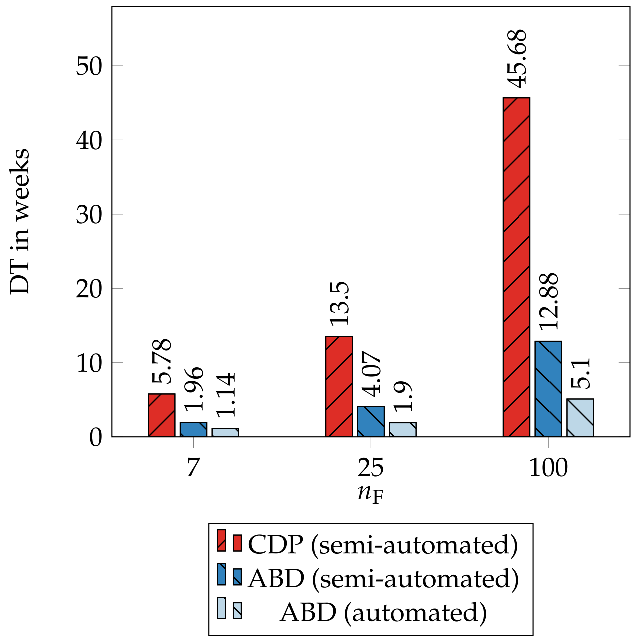


(**b**)

Figure 10. DT for both the CDP and ABD (**a**) with $n_{DO} = 1$, and (**b**) with $n_{DO} = 3$, depending on n_F for the BSD case study, in manual, semi- and fully automated design modes, with $\delta = 0.6$, $n_{TCpC} = 16$, and $n_{KDI} = 3$. In all ABD cases, n_{CpF} is corrected following (13).

Table 11. DT saved by ABD over the CDP for various n_{DO} and n_F values, with $\delta = 0.6$, n_{CpF} corrected following (13), $n_{TCpC} = 16$, and $n_{KDI} = 3$. In automated mode, the fully automated ABD is compared to the semi-automated CDP.

Design Mode	n_{DO}	n_F	DT Savings in ABD
Manual	1	100	36%
Manual	3	100	78%
Semi-automated	1	100	49%
Semi-automated	3	100	72%
Automated	1	100	70%
Automated	3	100	89%

With large n_F values, the DT becomes critical, provided the current TtoM requirements. For $n_F = 100$ (typical value for automotive gearbox designs), the CDP, with manual design (e.g., for R&D purposes), becomes unrealistic. The D must then use alternate design processes, such as concurrent engineering.

9.2. Number of Technical Checks TC and KDI (n_{TCpC} and t_{KDI})

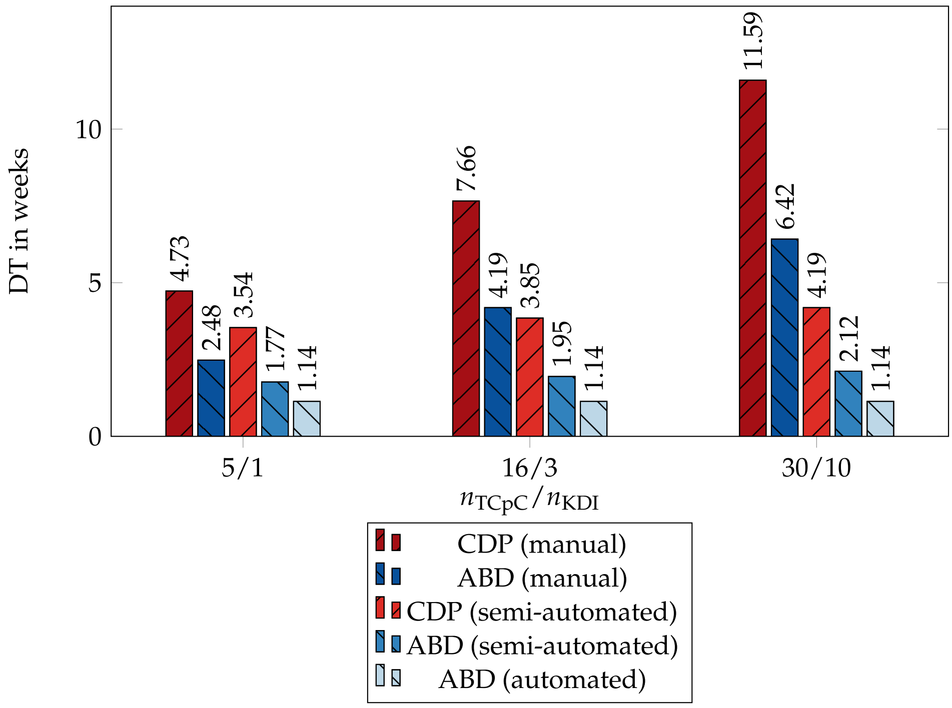
A second sensitivity analysis was performed on n_{TCpC} and n_{KDI}. In this context, the number of technical checks and KDI were varied simultaneously as they respectively represent local and global technical verifications. The following notation was used to identify their respective amounts: n_{TCpC}/n_{KDI}. For example, in the BSD case study, 16 TC and 3 KDI were considered, hence the 16/3 notation for the number of these technical computations. Both parameters were varied within the following discrete list of values: 5/1 (i.e., low technicity), 16/3, and 30/10 (i.e., high-tech design).

Figure 11 shows the CDP's and ABD's DT for different values of n_{TCpC} and n_{KDI}, all other conditions remaining constant.

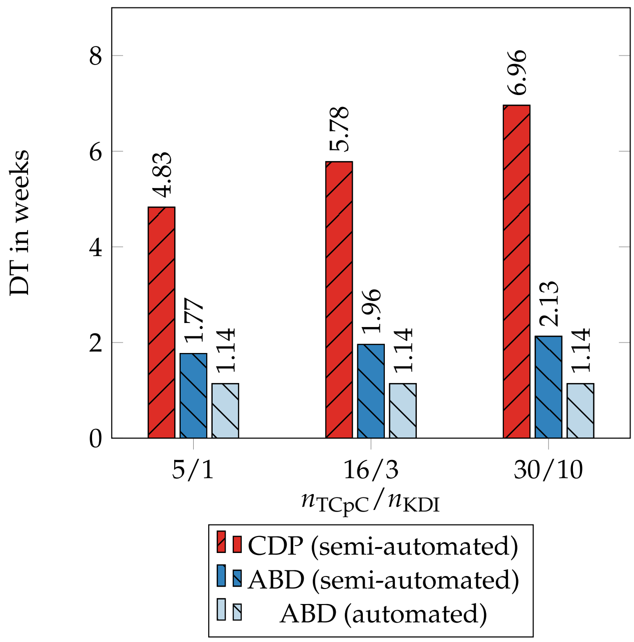
The relative design time gain is summarized under various conditions in Table 12. This gain tends to increase when the required n_{DO} is larger.

Table 12. DT saved by ABD over the CDP for various n_{TCpC} and n_{KDI} values, with $\delta = 0.6$, n_{CpF} corrected following (13), and $n_F = 7$. In automated mode, the fully automated ABD is compared to the semi-automated CDP.

Design Mode	n_{DO}	n_{TCpC}/n_{KDI}	DT Saving in ABD
Manual	1	5/1	48%
Manual	1	30/10	45%
Manual	3	5/1	70%
Manual	3	30/10	77%
Semi-automated	3	30/10	69%
Automated	3	30/10	84%



(**a**)



(**b**)

Figure 11. DT for both the CDP and ABD (**a**) with $n_{\mathrm{DO}} = 1$, and (**b**) with $n_{\mathrm{DO}} = 3$, depending on $n_{\mathrm{TCpC}}/n_{\mathrm{KDI}}$ for the BSD case study, in manual, semi- and fully automated design modes, with $\delta = 0.6$, and $n_{\mathrm{F}} = 7$. In all ABD cases, n_{CpF} is corrected following (13).

10. Conclusions

The CDP does not guarantee that a satisfactory design can be delivered within the specified time limits because of its sequential approach. Moreover, if a DI is unsuccessful, no DO is found, and a new DI must be started without any certainty of success. Nowadays, competitive environments put the TtoM under drastic pressure, reducing it to figures of the same order of magnitude as the DT [45,69]. Designing, conceptualizing, selecting the right components, checking their performance and safety, and synthesizing the required documentation are complex and intensive design tasks that require time and maturity (design and TC account, respectively, for 12% and 56% of manual DT). Using the CDP in time-constrained, versatile environments poses a high risk of failure of the design process.

ABD was developed to address these issues and reduce design risk in modern, competitive environments. It was focused on standard component sub-assemblies designs. It has eight main steps, and it integrated delivery constraints at the earliest stage of the design process.ABD integrates delivery constraints at early stages of the design process itself, filling a gap in the CDP ("over the wall" approach [17,55]).

To quantify ABD's performances, both design processes were thoroughly analyzed and compared. Timeline models, based on the main steps the designer must achieve, were established for both CDP and ABD design processes. Since design success depends on the availability ratio of selected components (δ), a probability approach allowed us to estimate the required n_{CpF} to successfully generate an available DO.

To practically evaluate ABD, an industrial case study of a BSD was considered. The characteristic durations of each design step were carefully taken from industrial design practice, considering manual, semi-automated, and fully automated design.

The DT were evaluated for both design processes CDP and ABD and led to the following conclusions:

- In the CDP performed manually, the TC and KDI calculations amount to 56% of the DT
- In CDP performed manually, the availability check takes 24% of the DT; reducing those durations using automation can bring a decisive strategic advantage to the D
- ABD, performed manually, offers a significant DT gain over the CDP, which has been quantified in the BSD case study:
  - The influence of δ, including for exceptionally low values (shortage, $\delta \leq 30\%$), was studied, and ABD performed better under these conditions;
  - Specifically at high availability ratios (full availability, $\delta > 80\%$), when the design process is performed manually, CDP becomes more efficient than ABD;
  - For multiple DO, ABD remains more efficient than the CDP.
- Semi- or fully automated design modes strongly improve the performance gap between ABD and CDP, even if both methodologies are automated (the CDP cannot be automated beyond the semi-automation state). In these design modes, conclusions similar to the ones in manual design can be drawn:
  - Lower availability ratio values strongly favor ABD over the CDP;
  - At high availability, the CDP may become more efficient than ABD in semi-automation, but not in full automation;
  - For multiple DO, ABD is always more efficient than the CDP.
- Sensitivity analyses were performed over two major parameters (the number of families n_{F} and the number of TC and KDI to be computed. In both cases, ABD always performed better than the CDP, and always more so as the automation degree improves.

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Qualitatively, ABD improves the performance of the D drastically by providing a set of available DO that satisfy the specifications. This allows a larger window of discussion between the D and the PM. It reduces unplanned risks significantly in today's highly competitive environments.

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Conflicts of Interest: Pierre Dupont is employed by Schaeffler Belgium, whose software is mentioned, among other developers' software, in the paper. Although mentioned, this software is not the core of the paper. The paper, instead, demonstrates the benefits of a new design methodology that leverages a class of software. No funding was requested to support this research. No third party influenced the contents of the paper in any aspect, nor its submission process.

Abbreviations

The following abbreviations are used in this manuscript:

AS	Associated services
BOM	Bill of Materials
CDP	Conventional Design Process
D	Designer
DI	Design Iteration
DO	Design Option
DT	Design Time
ERP	Enterprise resource planning
ETO	Engineering to Order
KDI	Key Design Indicator
MOQ	Minimum order quantity
PM	Project Manager
SB	Subassembly
TC	Technical Check
TPT	Total Processing Time
TtoI	Time to Invest
TtoM	Time to Market

Appendix A. Retroaction Loops and Their Circumstances

In both processes, retroaction loops have been identified and numbered as shown in Figure 3. Examples of circumstances that would activate these loops are detailed in this Appendix, both for the CDP and ABD.

Appendix A.1. Conventional Design Process

Loop 1 The suggested concept does not meet the specifications; the concept must be started over.

Loop 2 The design fails to meet the concept using standard components; the concept must be adapted.
Loop 3 Not all components satisfy the TC; components must be changed at the design stage.
Loop 4 No component satisfies the TC; the concept must be altered.
Loop 5 Alterations of the concept still do not allow meeting the TC; the specifications must be negotiated and adapted.
Loop 6 The delivery time cannot be met; negotiations must occur with the supplier if the delay margin is sufficiently small.
Loop 7 The delivery time cannot be negotiated to meet the requirements; the design must be changed.
Loop 8 The design changes do not yield an available DO; the concept must be changed.
Loop 9 The concept changes do not yield an available DO; the specifications must be negotiated and adapted.

Appendix A.2. Availability-Based Design

Loop 1 The suggested concept does not meet the specifications; the concept must be started over.
Loop 2 The designs fail to meet the concept using standard components; the concept must be adapted. In ABD, several designs are generated and investigated simultaneously, minimizing the probability of occurrence of this loop.
Loop 3 None of the selected components is available. In ABD, the number of selected components can be adapted to account for the availability of components through Equation (13), minimizing the probability of occurrence of this loop.
Loop 4 No pre-selection can be made, e.g., because the TC results are insufficient. The design space (n_{CpF}) must be extended. The initial selection of n_{CpF} components in each family limits the probability of occurrence of these issues, minimizing the probability of occurrence of this loop.
Loop 5 If increasing n_{CpF} yields no pre-selection, the concept must be adapted. This loop mainly risks appearing for an inexperienced D.
Loop 6 If a new concept with an adapted n_{CpF} yields no pre-selection, the specifications could be impossible to meet and must be adapted. This loop mainly risks appearing for an inexperienced D.
Loop 7 If the KDI requirements cannot be met, a new pre-selection must be conducted.
Loop 8 If the KDI requirements cannot be met with any combination of components listed at the end of ABD5, the design space must be extended.
Loop 9 If the KDI requirements cannot be met with an extended design space, the concept must be adapted.
Loop 10 If the KDI requirements cannot be met after adapting the concept and the design space, the specifications must be negociated and adapted.

ABD's loops 8, 9, and 10 are most likely to occur for an inexperienced D, or in overly complex designs where no standard solution exists.

Appendix B. Influence of δ over the DT for the Semi-Automated Process

Similar to the analysis of the influence of δ performed in Section 8.3, this Appendix shows that the semi-automated process increases the δ threshold over which the CDP is faster than ABD. Comparing Figure 8 with Figure A1 clearly shows how semi-automating the processes already benefits ABD. In full automation, even at full availability, ABD is always faster than the semi-automated CDP, which cannot be fully automated.

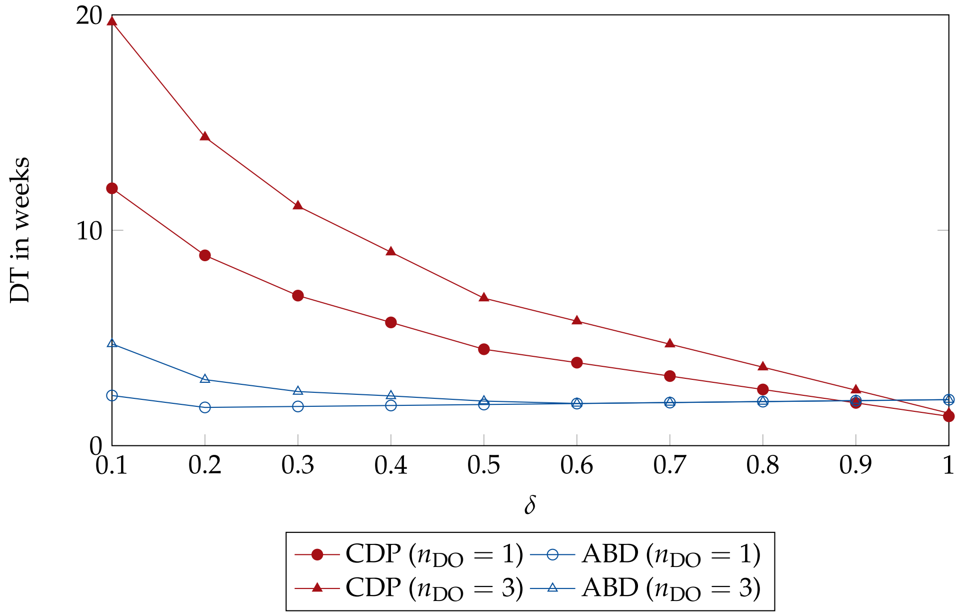

Figure A1. Variation of the CDP's (red, filled marks) and ABD's (blue, outline marks) DT with δ, for $n_{DO} = 1$ (circle marks) and $n_{DO} = 3$ (triangle marks). In all cases, the calculations are semi-automated, $n_F = 7$, $n_{TCpC} = 16$, $n_{KDI} = 3$. In all ABD cases, n_{CpF} is corrected following (13).

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