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Methodology for systematic design of cleanroom assembly workstations

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Abstract

Given the growth of cleanroom manufacturing for high-tech products and the high costs of operating within a cleanroom environment, an accompanying efficient manufacturing system is important. While abundant examples of efficient assembly manufacturing systems exist today, implementation of these into a sensitive cleanroom manufacturing environment has proven to be difficult. Against this background, this paper presents a transferable methodology to support the design of cleanroom assembly workstations which brings together aspects like cleanliness, ergonomics, modularity/flexibility and flow in an integrated manner. A set of guidelines was developed and embedded into a systematic procedure. The methodology was implemented and validated in a case at a high-tech precision manufacturing company, with high-mix-low-volume characteristics. The case study underlines the feasibility of the approach and the multicriterial improvement of workstation design towards the current state of the art. It also lead to a transferable cleanroom workstation design.

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Keywords: human centered factory; workplace design; cleanroom

1. Introduction

Cleanroom manufacturing has become an important issue over the last years and is likely to become even more relevant as technology advances and tighter controlled manufacturing environments are required. One driver is the rising demand coming from the electronics and semiconductor industry [1] that require to control the environment to certain standards [2] due to the contamination sensitive products. There are many factors that play a role in the manufacturing of high-tech modules in a cleanroom, but often the cleanroom assembly process is key. Innovative solutions in manufacturing associated with terms such as smart manufacturing or Industry 4.0, can enable an operation to improve its productivity and reduce errors and are an interesting prospect for the present and the future [3]. However, implementation of these ideas into a cleanroom assembly system should only be done once the fundamental design of a cleanroom assembly system is defined. In contrast to the design of assembly station in less sensitive environments and applications, cleanroom assembly includes additional and more complex requirements from different directions. Looking into the state of the art underlines that in general several separate supporting methods and guidelines exist, e.g. towards ergonomics [4], cleanliness [5] or lean production [6]. However, those perspectives and fields of action are rarely brought together to facilitate a holistic design. Thus, this paper aims at developing an integrated set of guidelines and a connected procedure that should be followed for designing a cleanroom assembly station. The methodology is implemented for the case of high-tech precision manufacturing company. This application resulted in a concept design of a cleanroom assembly station for manual

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precision assembly cleanroom products. The concept is to some extend specific while considering the boundary conditions of the company case – however, it is in general quite transferable to other cases in comparable contamination sensitive applications.

2. Methodology

2.1. Cleanroom workstation design procedure

Figure 1 shows the suggested procedure for the systematic design of cleanroom assembly workstations. It addresses company stakeholders like industrial engineers or shopfloor management that are responsible for the planning and improvement of production systems. Based on literature review and practical case analysis, guidelines were derived for four different fields of action (described in the following sections): cleanliness, ergonomics, modularity/flexibility and production flow/logistics (lean production perspective). Those guidelines were further broken down into eight criteria dimensions that serve as base for the assessment of the current situation but also later for the developed design concepts. Differing importance of the criteria is considered through introduction of weighting factors. Weighting factors are derived with established methods like AHP (analytical hierarchy process)/pairwise comparison. The resulting assessment leads to improvement actions and with further iterations eventually to the final design.

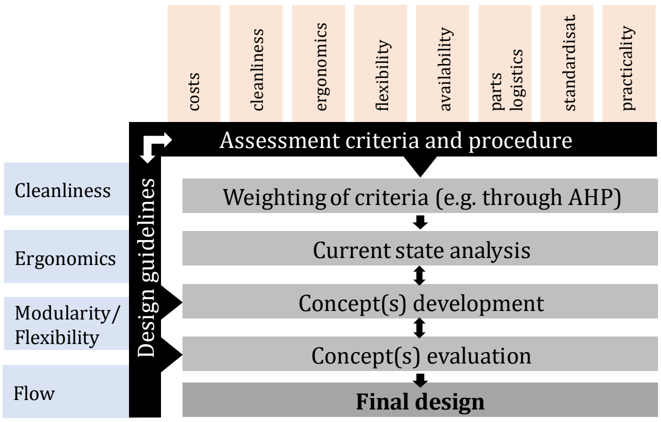


Figure 1: Procedure for systematic design of cleanroom assembly workplaces.

2.2. Cleanliness guidelines

The cleanliness guidelines were developed based on understanding how a contamination is created and controlled and how the cleanroom intrinsically works and the problems that come with it. The most important factor to consider is the role the human plays in contaminating the area. Every action performed by humans (e.g. breathing, walking, manipulating objects) will contaminate the area [7]. There are multiple sources of contamination, of which the main ones are particle contamination [8] and chemical contamination [5]. Particle contamination comes from the process of aging and friction. Everything that ages slowly releases particles, like human skin or hair. Friction happens during the assembly work (e.g. fastening bolts screws), but is inevitable. However, tools and products sliding over the workstation, must be minimized in order to keep the environment as clean as possible. It also puts limits on designs of the tool holders and part containers to create minimal friction. Chemical contamination is the contamination through processes like lubricating or gluing, which are typical operations in the cleanroom. To reduce chance of contamination from workstation to the product, surfaces must be regularly cleaned, so should be smooth and rounded. Another term used a lot is cross-contamination, which is the process of surfaces or substances touching one another and then something else and therefore spreading the contaminants. Materials are the next important consideration, which should be hard, as to not create much particles when equipment comes in contact with one another. The next important material consideration, is material outgassing, which will slowly occur over time and happens in polymer structures as well as metals, is unavoidable and can still be a detrimental form of contamination [9]. Materials that show little outgassing and do not react with other substances are therefore required. An example of an ideal cleanroom surface is stainless-steel, as it is hard, non-reactive and easy to clean. Stainless-steel is widely used in pharmaceutical and medical industry for these exact reasons. Cleanrooms work through controlling the contamination of air and surfaces to appropriate levels to perform contamination-sensitive activities. The environment is managed through a system of air filters, air outlets and air exhausts that circulate the air in a downwards moving stream from the ceiling towards the floor [10], like shown in Figure 2. This constant downstream of air drags particles and droplets with it in the most effective way, in the same direction as gravity.

However, this poses an intrinsic cleanroom problem as well that needs to be taken into account, which is that this constant downstream of contaminants ’rains’ on people, surfaces, equipment and products. Therefore it is standard procedure to cover products with plastic sheets while they are not being worked on, such that the products are not directly exposed to this stream of contaminants. It also means that in general, flat horizontal surfaces should be minimized in the design, as to make sure no contamination can accumulate on top of them. A combination of the effects of how contamination is created, how humans spread it and how the cleanroom airflow transports contamination, is that the an operator working at a workstation should in theory not move over the product, as it means that contamination will flow directly from the operator onto the product (Figure 2). During regular assembly work, this is not always avoidable, but the workstation design should not facilitate this behavior when reaching for assembly equipment or getting required information.

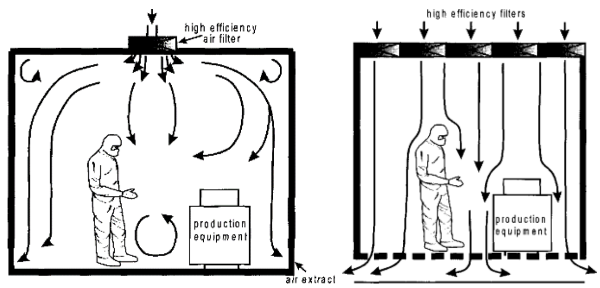


Figure 2: Different airflows (left: conventional, right: unidirectional) in cleanrooms and human interaction [10].

The combination of the basic principles and properties of cleanroom assembly as described above resulted in the set of cleanliness workstation design guidelines shown in Table 1.

Table 1: Cleanliness design guidelines.

C.1	There should be no equipment at the back of the workstation, especially not behind product
C.2	Products and all required assembly equipment should be covered when not in use
C.3	Obstruction of the downstream airflow should be avoided where possible
C.4	Avoid horizontal surfaces where possible
C.5	Horizontal structural elements should be cylindrical
C.6	Work surface material should be hard and non-reactive. Use stainless steel where possible.
C.7	Materials should show levels of outgassing lower then own defined standards
C.8	Every accessory must have a dedicated place so it can be stored and the table can be adequately cleaned
C.9	Friction creating elements such as sliding or rotating components should be avoided where possible

2.3. Ergonomic and safety guidelines

A good assembly workstation should keep the operator central as part of the design. This means that the design should be ergonomic and create safe working conditions for the operator. Improving ergonomics can also positively impact productivity [9]. In order to address ergonomic standards in the production assembly process, there are multiple key factors that need to be taken into account: Working height, work area, reach zones, lighting and adjustable of work equipment [4] [12] [13]. Table 2 encapsulates the most important aspects for an ergonomic design and has a focus on the high-precision assembly work. Naturally these guidelines can be different for work that is not in a cleanroom and for the use of complex fine-mechanical assembly. These guidelines focus on reducing stress, fatigue and the risk of errors and on benefiting productivity and concentration.

Table 2: Ergonomic and safety design guidelines.

ES.1	A sit-down/stand-up workstation should be positioned at 1125 mm
ES.2	Height-adjustable workstations are most desired in terms of flexibility
ES.3	Avoid work above 1500 mm and below 800 mm
ES.4	Keep work in the optimum reach zones
ES.5	Place most used and heavy assets closest to mechanic
ES.6	Light intensity for complex tasks should be between 1000-1500 lux
ES.7	Provide adjustable work equipment (chairs, shelves, arms, monitors) to ensure flexibility between people
ES.8	Provide modular components for footrests and armrests

As adaption from existing approaches (e.g. [4][13]), Figure 3 below shows a 2D implementation of guideline ES.4 in Table 2 and C.1 in Table 1. Average human reach zones are indicated, together with the area that shows were the operator should in theory not reach toward since there should be no equipment placed at the back of the workstation behind the product. Reach-zone A should be used for assembly operations with two hands and pure lower arm movements. Reach-zone B should be used to store parts and equipment that are frequently used and can be easily grabbed with one hand. Reach-zone C should be used as little as possible and can be used for assets that are not often used.

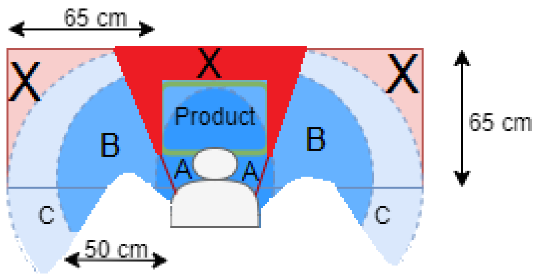


Figure 3: 2D reach zones regarding cleanliness and ergonomics.

2.4. Guidelines for modularity and flexibility

Modularity refers to "[…] machines, assemblies and components that fulfil various overall functions through the combination of distinct building blocks or modules" [14]. The term flexibility is encapsulated in modularity, since a modular system allows flexibility in the design through the combination of the different building blocks of a modular system. Flexibility is the ability to quickly adjust to the manufacturing environment, from different products, order size or production requirements and is the opposite of dedication seen in mass manufacturing. When designing for flexibility, preference should be given to technologies that are reconfigurable and reusable, over welded constructions for example [15]. In manufacturing industry, the most flexible and modular systems come from aluminum profile-based designs with smart fixtures. The benefits of these systems are that they can offer quick connection of standard elements and can build anything from standalone workstations to fully-automated assembly lines. Thus, this enables the ability of the individual and flexible configuration of workstations [6]. The modularity aspect of any design can be expanded to any part of the design, for example the tools. Having a modular system of tools, with specific holders for each tool that can be easily added or removed only adds to the flexibility of an assembly station [15]. Table 3 shows the identified guidelines regarding modularity and flexibility of a workstation.

Table 3: Modularity and flexibility guidelines.

MF.1	The design should consist of standardized modular elements
MF.2	Standardized elements should be easily reconfigurable or interchangeable
MF.3	The design should incorporate flexible/ movable components to account for changes in product size or people
MF.4	The construction of the design is ideally build from aluminium profile technologies

2.5. Guidelines for increased flow

Guidelines focused on a workstation for increased flow of products and for workstations that can be placed in an assembly cell very much concern the assembly system as a whole. Principles from lean manufacturing can help in reducing the 7 main types of 'Muda', or waste in Japanese. As a result, lean practices can increase throughput, reduce inventories and number of errors to name but a few benefits [16] [17]. One of the lean practices considered with design guidelines for flow, is single-piece flow of products. In order to facilitate single piece flow, commonly used operations and practices that go with it are 2-bin Kanban systems and Water spiders. A Water spider is known as a person who timely resupplies materials as a way to improve internal logistics and reduce waste in the form of Work-In-Process [18]. Another important aspect is the visual management of all the required assembly equipment, through the use of shadow-boards or tool inlays for example. In other words this can be said to be organizing the assembly station, which can be achieved with 5S and as such improve the operation [19]. Furthermore, flow is also experienced on the workstation itself, considering the speed at which assembly takes places and the flow of parts on the workstation. Considering flows in a cell, which are typically set up counterclockwise [20], the same principle can be followed on the workstation itself. In that regard, you would store parts mostly to the right, and finished products to the left. However, the placement of assets and equipment is not just dictated by flow, but also by ergonomics and assembly speed. A proven way to measure the time it takes to perform operations and find the optimal placement arrangement of equipment is the methods-time measurement (MTM) [21]. Implementation of this method can be used as an advanced tool in delicately determining the placement of each equipment, as it takes into account the time it takes to perform basic motions like grabbing, reaching, picking up, placing down etc. Since this method is so advanced, the simple translation of it is to place the assets that are used most closest to you, as the basic motions are performed most often, and less used assets further away. Table 4 shows the representation of the learning's into the set of guidelines belonging to increasing flow.

Table 4: Guidelines for increasing flow and assembly line workstations.

F.1	Workstations should be able to be easily placed in an assembly cell at a fixed height
F.2	Only provide the exact required equipment
F.3	Allow little to no space for WIP-storage on the workstation itself
F.4	Minimize reaching distances and place most used assets closest by operator
F.5	Visually represent where assets should be (shadow-boards, inlays, markings, labels)
F.6	Materials in assembly cells should be fed from the outside/backside
F.7	Ensure counterclockwise flow/work patterns (most used items right, less used to the left)
F.8	Strive for one bin system to reduce space needed

3. Industrial case study

Implementing the design guidelines for a cleanroom assembly workstation into a practical case is ultimately the best way to evaluate them and to ensure that a new design following these guidelines would be better than a current situation. In order to come up with a concept design, it was important to not look at just the workstation, but the assembly system as a whole.

Current state analysis

In order to start assembly, a mechanic will first have to gather the parts, where there is a difference in order picked parts, and so called grab-stock. Order picked parts are selected based on the production order from within the factory and are already sorted for the mechanic in a box. Grab stock consists of standard fasteners and washers, that are stored in a warehouse within the cleanroom. If the assortment box is empty, a mechanic will have to restock these himself from this warehouse. Once he has all the parts he can bring these two boxes to the workstation where the order picked parts will first have to be unpacked from a plastic wrapping, that ensures the parts are clean. Once he has all his equipment ready, a paper map with the exact assembly instructions will guide the mechanic through the steps to assemble a product, which could mean cleaning of the workstation and equipment in between operations. In order to do that, we can look back at cleanliness guideline C.2 and C.8 in Table 1, in which it is stated that equipment must be adequately stored and must be able to be covered, so the workstation is clear of obstruction and can be easily cleaned by a mechanic. Once a product is assembled it might still need to be tested and qualified, and then that data needs to be logged on a computer, that is often not available at a workstation, but is shared among mechanics. The finished parts are stored away and the process is repeated. A typical workstation is shown in Figure 4 which also highlights some of the shortcomings:

- **Ergonomics**: No sit-stand flexibility, but fixed sitting height (800 mm). Tables are (too) deep. Shelves over the head with equipment cannot be reached without standing. Light is blocked by shelves and mechanic so creates shadows directly over the product.
- **Cleanliness**: The shelves collect dust. Tool cart drawers slowly accumulate contamination but cannot be easily cleaned and therefore are not. The workstation does not promote regular cleaning, since equipment does not have a dedicated spot that is visually represented. Storing equipment at the back of the workstation means that a mechanic must reach over the work surface and will contaminate it in the process. The current tool holders are made of metal, giving metal on metal contact every time a tool is used which in turn creates particles. The lighting construction and other components directly obstruct or affect the downward flow of air.
- **Structure**: The lack of visual management and organization of equipment means tools go missing and creates frustration among workers. There is no dedicated layout for all the workstation that dictate the spot for all assembly accessories.

- **Practicality**: There is generally no access to a computer to log data on the workstation. The way tools and other equipment are stored is chaotic. There is not always a lightbar at the workstation.
- **Parts logistics**: Getting grab-stock and order picked parts cannot be done in one trip.
- **Flexibility**: All workstations are fixed in design and not made of modular, easy to reconfigure components, which means design freedom is limited and a workstation cannot be individually configured to the specific needs.

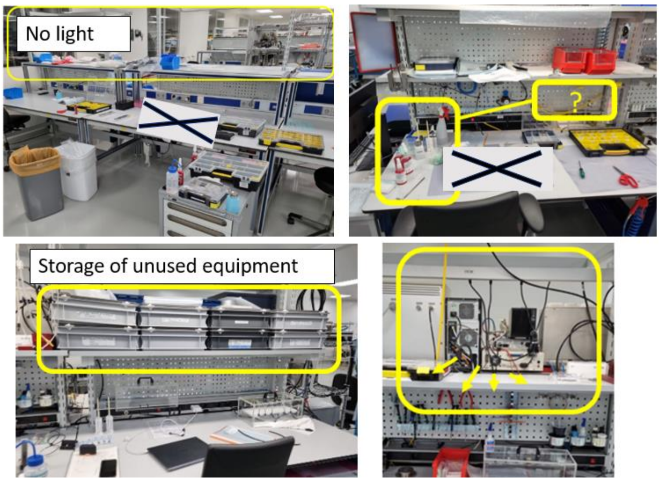
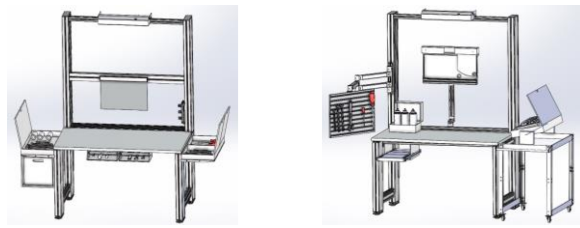


Figure 4: Exemplary cleanroom workstations from company case.

Concept development
Figure 5 shows two developed variants for the cleanroom assembly workstation which differ regarding the type and extend of considered guidelines. Concept 1 should have a stainless steel tabletop, with the required equipment stored on modular brackets on both sides of the workstation (parts on the right in the assortment boxes, tools and cleaning materials on the left with a cover). The tools will be stored in a 3D printed inlay and stand upright, allowing for dedication of the tools per workstation and minimize required space. A similar 3D printed inlay is made for the cleaning equipment that can be standardized since all workstations require the same cleaning materials. Underneath the tooling and cleaning bracket is a drawer, that can store specific tooling like clamps and jigs that are made in-house and are too big for the inlay. A pull-out shelve provides access to information. This configuration allows for height adjustability. A light strip is presented at the back as to not obstruct the natural airflow in the cleanroom and still give good lighting.
Also the second concept (concept 2) should include a stainless steel tabletop, with parts provided on a standard trolley with a slideable and tilt-able tray. Tools hanged on a (shadow-)board that allows for a small movement to get it closer to the operator. There is a fixed and standardized box for the cleaning material on the workstation, that works can be closed by pulling the underside up. An open drawer unit is placed underneath the tabletop that can house the specific tooling that will not fit on the tool board, but will have a fixed inlay on this drawer unit. A pull-out shelve provides access to information. This concept will have a fixed height due to the cart. A light strip is presented at the back as to not obstruct the natural airflow in the cleanroom and still give good lighting.

Concept 1	Concept 2



Cleanliness	
C.1, C.2, C.3, C.6, C.8, C.9	C.1, (C.2), C.4, C.6, C.8
Ergonomics	
ES.2, ES.3, ES.4	ES.1, ES.3, ES.4, ES.7
Modularity & Flexibility	
MF.1, MF.2, MF.4	(MF.1, MF.2), MF.3, MF.4
Flow	
F.1, F.3, F.5, F.7, F.8	F.3, (F.4), F.5, F.7, F.8

Figure 5: Different developed concepts and applied guidelines.

Concept evaluation
Based on the assessment of six different stakeholders (e.g. engineers, cleanroom workers) for the current and two new concepts, Figure 6 shows the (unweighted) results for the introduced assessment criteria. Quite clearly both new concepts can lead to significant improvements in most criteria whereas concept 1 resulted in the highest overall score. The current concept has only (obvious) advantages in terms of availability and costs since no additional efforts are necessary. Potential improvements through the new design were even more confirmed with the introduction of weighting factors. Figure 6 is sorted according to the ranking of assessment criteria. Cleanliness, ergonomics, practicality and standardization are among the most important criteria and both new designs lead to clear improvements here.

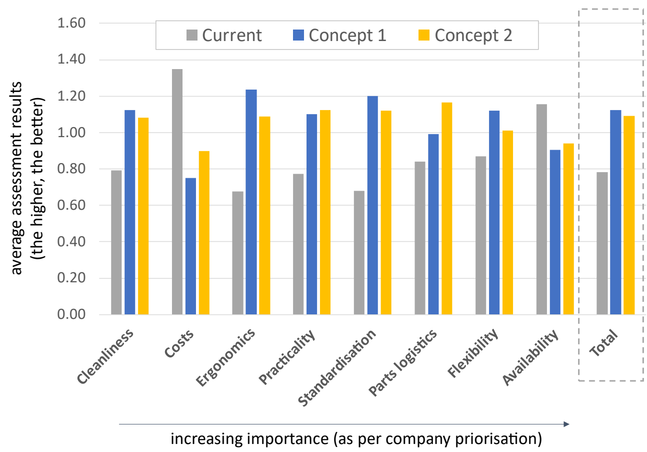


Figure 6: Assessment results for workstation designs (unweighted).

Final redesign
The previous assessment gave interesting insights into the overall favorability but also specific items of interest. As one example, Concept 2 scored well on the section called 'Parts

Logistics', and that came from the idea of introducing a parts trolley. The consensus was that integrating the parts trolley into Concept 1 was the most favorable outcome as final design scenario. Figure 7 shows the final workstation design. The parts cart or kit-cart, can be driven into the workstation and be locked in place by a pin. The workstation allows for height adjustability, because the trolley can be fixed in place, and should be driven into the workstation when it is completely lowered. The U-shaped cutout can be made possible by the use of extruded aluminum profile technology. If a flexible supplier can be found from aluminum extruded profiles, then this U-shape could have an opening at the front or at the back. A cut-out at the back allows quick re-supply, potentially by a water spider in an assembly cell, to facilitate continuous assembly. The kit-cart can then mount a similar modular frame as explained in Concept 1.

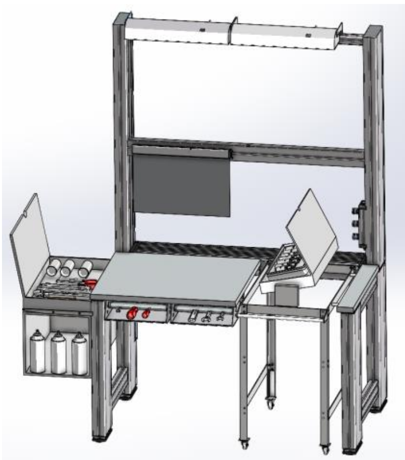


Figure 7: Final design of cleanroom assembly workstation.

4. Summary, Discussion and Outlook

This paper provides insight into the fundamental design principles for cleanroom workstations. These insights were transformed into design guidelines, not only related to cleanliness, but also other relevant workstation characteristics. The derived design guidelines led to the development of a cleanroom workstation concept design, specifically based on the needs of a high-tech precision manufacturing company. According to the multi-criterial assessment this design leads to clear improvements compared to the current state. The new design obviously orients on the boundary conditions of the considered company but is also quite transferable to comparable cases. In any case, the derived guidelines support a systematic design process.

For further steps, more test validity tests of the design guidelines should be conducted. Another interesting field of research is the expansion of the cleanroom and cleanliness design guidelines for an assembly workstation, that clearly distinguishes the guidelines for different classifications of cleanroom. In that way it could set industry standards for the design of cleanroom workstations for different cleanroom classes. This does not have to be limited to workstations only, but could also include more specific guidelines e.g. for automated assembly systems.

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