ESC102 | Request for Proposal

Less Chaos, More Construction - A LEGO Brick Sorting Solution

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Abstract

This Request For Proposal investigates the challenge of sorting LEGO bricks, and proposes the development of an automated sorting system.

ToroLUG, a Toronto-based community of Adult Fans of LEGO (AFOLs), frequently encounters this challenge, with members reporting that sorting consumes more time than building. Existing solutions, including the official LEGO Sort and Store, fail to meet their needs due to limited sorting capabilities and a reliance on manual labour [49, 38]. Other available designs have larger dimensions and weight than ToroLUG AFOLs would want, hindering the usability of the design [51, 52].

Based on stakeholder input, the design must be a compact, automated system that can sort LEGO bricks by type, colour, or size according to user preference. To ensure safety, it must not have exposed moving parts, must include an automatic shutoff and must not have any sharp edges. Additionally, the sorting shall also require no user's help during operation, provide sorting for 4 feature specificities, have a maximum cycle time of 3 seconds and a minimum accuracy of 80% for the usability and performance of the design.

The design requested by this RFP shall fill the gap between the users' needs and the existing solutions, with a design that prioritizes the usability, performance, and safety of the user, enabling them to spend less time sorting and more time building.

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1. Introduction

This RFP solicits solutions for an automated LEGO sorting system to help the Toronto LEGO User Group (ToroLUG) organize their collections. Adult Fans of LEGO (AFOLs) accumulate vast brick collections, making sorting a time-consuming process that limits creative building time. This document defines key stakeholder needs, establishes design requirements that address usability, performance, and safety, and outlines why existing solutions fall short with these requirements.

2. Background

Understanding ToroLUG as a LEGO community is crucial for making informed design decisions. This section introduces LEGO user groups, common community terminology, and the community of focus, ToroLUG.

2.1. The History of LEGO Fan Groups

LEGO has built a global community of adult fan groups for over 30 years by providing the building blocks to allow them to explore their creativity [1] (Appendix C, Figure 1). These groups provide opportunities for collaboration and the sharing of innovative building techniques.

ToroLUG, the Toronto LEGO User Group, is an example of a LEGO community that nurtures creativity and teamwork in LEGO-based design (Appendix A, Figure 1). They achieve this sense of creativity and community through providing a structured space both in-person and online for skill-building, large-scale projects, design challenges, and public showcases [2] (Appendix C, Figure 2).

2.2. LEGO Community Terminology

Abbreviations used commonly in the LEGO community and in this document are explained below:

- LUG: LEGO User Group, i.e., an organized group of LEGO users [3].
- AFOL: Adult Fans of LEGO, i.e., fans of LEGO above the age of 18 [4].
- MOC: My Own Creation, i.e., models designed and built by AFOLs [5].

2.3. ToroLUG: A Community of Adult LEGO Enthusiasts

ToroLUG is a Toronto-based AFOL community that fosters creativity and collaboration through both online and in-person engagement. AFOLs connect via Discord to showcase MOCs and chat, while also meeting monthly at local showcases, events, and competitions (Appendix A, Figures 2–5).

To ensure that the community is a safe and democratic place, it is regulated with formal by-laws and an executive committee elected annually by members (Appendix A, Figure 3). They list all rules and regulations of their community in their official Discord server, which has over 140 members.

As most members build MOCs in personal workspaces, we framed this RFP to design for a personal LEGO sorting device over a communal one. This allows users to sort their LEGO bricks according to their individual preferences, better suited to their building habits and designs.

3. Why LEGO Sorting as an Opportunity?

In this RFP, we refer to sorting as it is defined in the Cambridge Dictionary- "sorting something into something". Here, we are sorting LEGOs into specified categories [6] (Appendix C, Figure 3).

An AFOL can accumulate thousands of LEGO pieces over years of collection, such as in Figure 1, and a large variety of types of LEGO bricks can make it harder to find certain pieces for MOCs. With over 60 official themes and around 4000 unique LEGO elements [7] (Appendix C, Figure 4), finding specific pieces can become difficult. Not to mention, according to former LEGO ambassador David Eaton, AFOLs can have anywhere between 10,000 to 1,000,000 LEGO pieces [9] (Appendix C, Figure 5). With such a large volume of bricks, manual organization quickly becomes challenging.

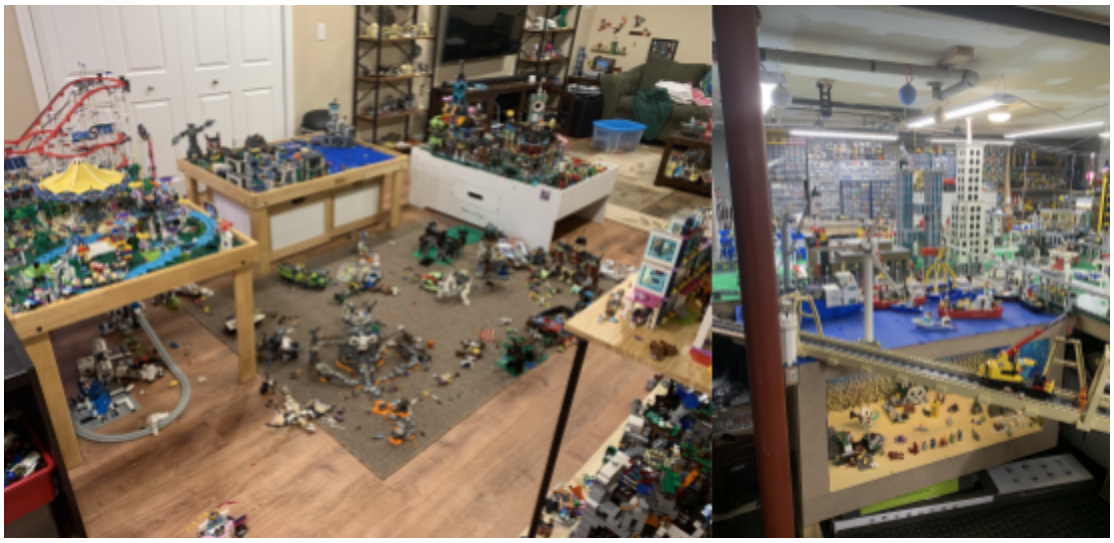

Figure 1. Pictures of the home of an AFOL, Liz Puleo. Married with kids, she converted their basement into the "family LEGO haven," filling the place up with sets and creations [8].

For an AFOL, an MOC is their LEGO-related creative outlet, which is why it is important for them to have access to the LEGO bricks they want. JMB Samon, author of JMBricklayer, emphasizes that "MOCs hold immense importance [to LEGO fans]" [10] (Appendix C, Figure 6). As shown in Figure 2, a typical ToroLUG MOC can span an entire table, making quick access to pieces important for the building process [11].

Figure 2 - Screenshot from ToroLug official Instagram page, sharing a MOC that is almost as wide as the table [11]. There are numerous detailed LEGO and electrical components, including LED lights, incorporated into the design.

While MOCs are central to AFOLs for expressing creativity through LEGO, sorting can become a major obstacle for creators before they can start building. Many, balancing employment with LEGO as a hobby, are reluctant to spend excessive time sorting (Appendix B, Figure 3). One member expressed frustration, stating that "⅔ of [their] time is spent sorting, and only ⅓ is spent building," emphasizing the need for a solution (Appendix B, Figure 4). Additionally, older AFOLs may face vision or dexterity challenges, making sorting a physically and mentally straining task [12] (Appendix C, Figure 7).

ToroLUG members report a lack of effective sorting tools, with one member stating they've "tried various tools to help with sorting and so far almost all fail" (Appendix B, Figure 1). For example, the LEGO Sort and Store (see Section 7.1), the only official LEGO sorting product, has been criticized as inadequate for adult users. ToroLUG members claim that "it was a complete failure", and they prefer tools that are "more sophisticated and less general than what a child might build" (Appendix B Figure 1-2). Therefore, the information provided in this RFP, coupled with the requirements framework outlined, serve as the basis for a design that better meets the needs of ToroLUG members.

4. Stakeholders

This RFP considers an opportunity that aims to sort LEGO bricks quickly and conveniently– therefore, in this section, we describe the stakeholders of this design and how saving time and effort in sorting would help them.

4.1. The ToroLUG Community

The primary stakeholders of this opportunity are the AFOLs of ToroLUG, who introduced this opportunity by expressing their frustration in handling large volumes of LEGOs at once. They work on complex MOCs, as shown in Figure 2, that require quick access to specific pieces. One ToroLUG member claimed that "[they] don't like sorting … so the task is a necessary evil for [them] to enjoy the hobby" (Appendix B, Figure 5). Designing a LEGO sorter, with ToroLUG members' needs in mind, will reduce the time and energy that AFOLs spend sorting, leaving more time for ideation and creation.

4.2. Other AFOLs

Large-scale MOCs are common with AFOLs outside ToroLUG as well. Figure 3 shows an excerpt from Rebrickable, a website dedicated to AFOLs who wish to share instructions for building their MOCs, many of which are detailed, time-consuming projects [13].

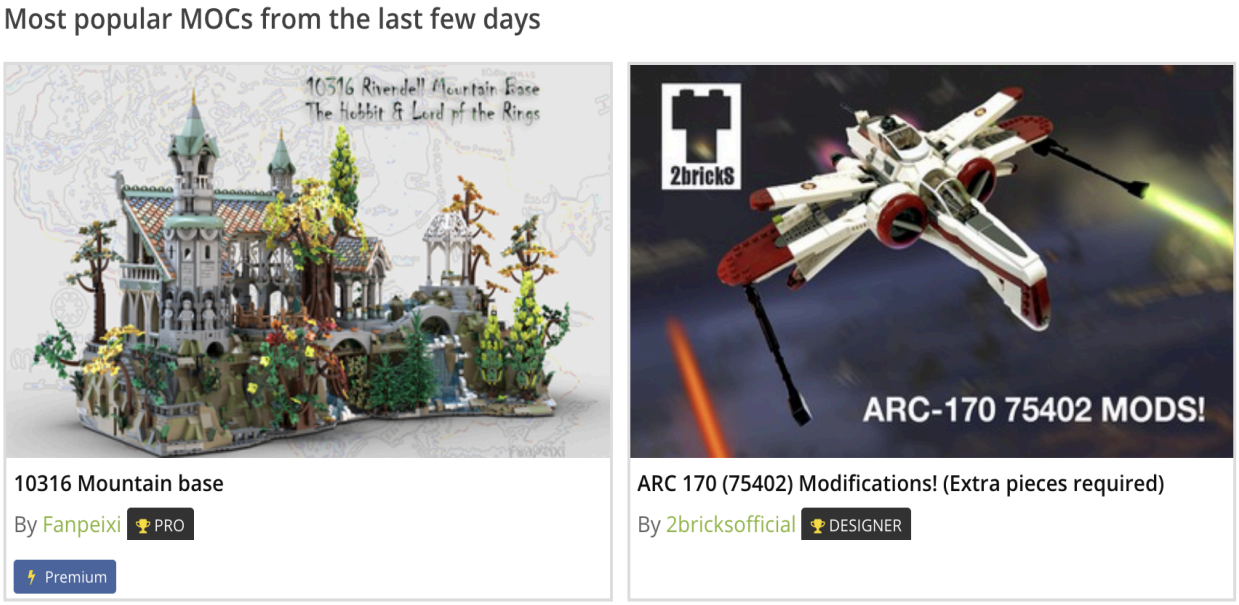

Figure 3 - An excerpt from Rebrickable, showing some examples of MOCs created by AFOLs [13].

These large-scale projects often require vast quantities of LEGO bricks, leading to a common challenge: sorting. AFOLs on online forums say they are in "serious need of a sorting strategy", and "wish there was a LEGO sorting machine" [14] (Appendix C, Figure 8; Appendix C, Figure 9). A survey by Brick Architect found that as LEGO users age, and transition into AFOLs, they prefer sorting by *some* category– usually part, or part and colour [15] (Appendix C, Figure 10). A LEGO sorting system could address this common issue across the AFOL community, and allow them to spend more time building than sorting.

4.3. Parents and Teachers of Young LEGO Users

Parents and teachers of LEGO users may also benefit from a LEGO sorter, as it reduces clean-up time after play and learning. A family blog post addresses a certain "stage" in owning LEGO as a parent, noting that before long, "[their] house [began] overflowing with LEGO" [16] (Appendix C, Figure 11).

This can also be seen in Figure 4, where one family shared a picture of their children's unorganized LEGO sets. Reducing the effort expended in sorting can allow for a less strenuous childcare or teaching experience.

Figure 4 - The playroom of a family with four children. The mother describes that "[she] could write a book on Lego organization and the methods we've tried, to no avail" [17].

Furthermore, teachers using LEGO in classrooms often struggle to reset quickly between lessons. A LEGO Education blog notes that teachers who start the year with neatly sorted LEGO kits soon find their classrooms looking like a "junkyard", highlighting the common challenge of sorting within limited time [18] (Appendix C, Figure 12). This issue extends to educators who use LEGO for engineering and robotics, like the First LEGO League [19].

Notably, a solution being used around children must also prioritize safety, so that carers feel confident in using it around them, considering children may have decreased awareness of the potential dangers of an object compared to AFOLs. More details on safety are discussed in 6.2.3.

4.4. Makerspaces and Public Places for LEGO Building

Makerspaces and public places for LEGO buildings are creative environments, often found in schools, libraries, and community centres, where individuals engage in hands-on learning and play with LEGO bricks [21].

Makerspaces can struggle with keeping LEGO collections organized due to shared use. As shown in Figure 5, pieces often get scattered across tables, making it difficult to find parts quickly. Cary Busby, author of STEM Education, notes that "sorting can slow down creativity and innovation" [22] (Appendix

C, Figure 13). An automated sorting device could help address this issue by categorizing pieces before storage.

Figure 5 - A LEGO Makerspace [20], showing communal LEGO pieces scattered across a shared table.

Similarly, public LEGO event venues like *Bricks in the Six* or *LEGOLAND*, may face similar challenges [23, 24]. Cleaning up after sessions can be tedious for workers at public LEGO spaces, since organizing pieces from large unsorted piles can become very challenging. An automatic LEGO sorter would save time for staff by reducing manual sorting and improving access to pieces that have been used by the public.

4.5. LEGO Recyclers

A LEGO sorter may also benefit LEGO donation programs, such as LEGO Replay, where the LEGO corporation donates bricks to those in need [25]. As shown in Figure 6, LEGO accepts nearly all types of bricks – they don't need to be pre-packaged as per their standard sets (Appendix C, Figure 14). Sorting donated LEGO manually is time-intensive for workers and can be prone to human errors. Hence, mis-matched and faulty bricks in donation piles can be overlooked due to human error. A LEGO sorter that can differentiate between usable and defective pieces would save workers time and improve the quality of donations.

Figure 6 - Image of a sample box that can be donated to LEGO Replay, full of unsorted bricks, that will take time to sort through [26].

4.6. Our Praxis Design Group

As potential designers, we are stakeholders in this project, who will impact the creation of a LEGO sorter. Furthermore, having grown up with LEGO, we are familiar with the challenges of sorting, which makes us empathetic to the stakeholders of the opportunity. The complexity and designability of the design of the LEGO sorter, thus, is our vested interest.

5. Positionality

Our team realized that our initial assumption about ToroLUG being more about building was biased, and there were more to ToroLUG's values than we thought. We initially approached ToroLUG with a "physical-prototype" mindset, assuming that the most promising Praxis II opportunity would arise from the engineering and design aspects of LEGO. However, through community engagement, we realized that LEGO building is equally about creativity as it is about technical construction. In their official "About Us" section, ToroLUG emphasizes celebrating creativity and community through the art of LEGO building rather than purely focusing on engineering aspects [27] (Appendix C, Figure 15).

To prevent our assumptions from skewing our understanding of potential opportunities, we structured our outreach to be as open-ended as possible. We asked questions about members' day-to-day experiences with LEGO, rather than focusing solely on the physical act of building, allowing us to uncover broader frustrations and inefficiencies before narrowing our scope to sorting. As we refined our focus to LEGO sorting, we welcomed open-ended feedback, ensuring that members could share concerns beyond our predefined questions. We suggest that, going forward with this opportunity, the same option of open-ended responses being given to ToroLUG members, lest any other biases prevent designers from overlooking crucial design prospects.

6. Requirements

This section details the goals and objectives that enable a design to meet the need of our principal stakeholders, ToroLUG. It outlines the necessary features of a potential design, and justifies each constraint that the design must follow.

6.1. Graphical Representation of Stakeholder Needs

To facilitate a broad understanding of the requirements of the solution, we present a graphical representation of the needs, goals and objectives of this opportunity.

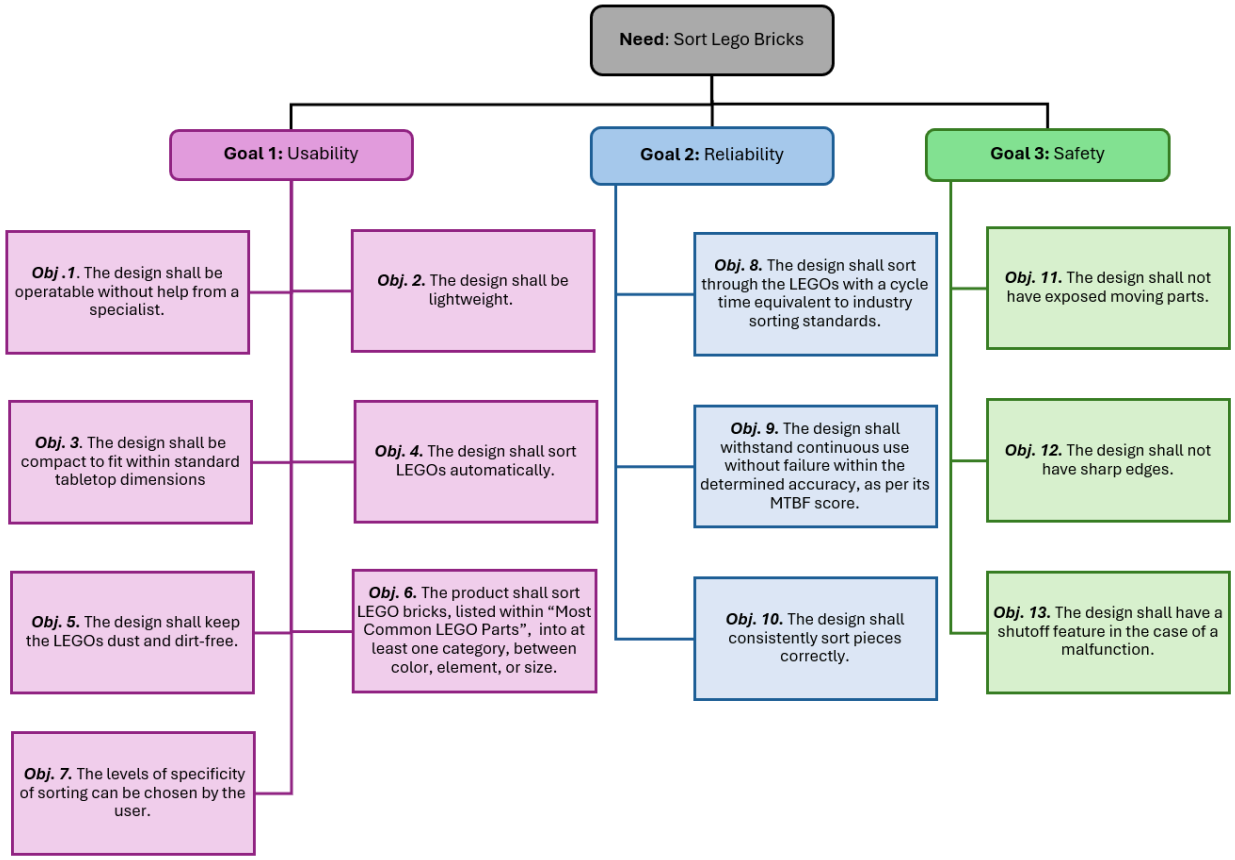

Figure 7- A graphical representation of the needs, goals and objectives hierarchy, tracing how each are connected. Based on this simplified graphic, the design should balance usability, performance, and safety to primarily meet the needs of ToroLUG users, and secondary stakeholders as mentioned in Section 4.

6.2. Requirements Framework

In this requirements framework, we outline the goals and objectives the design must satisfy in order to meet the need of sorting LEGO bricks. The framework details specific, measurable criteria for evaluating the system's usability, performance, and safety. These criteria are based on stakeholder needs and industry standards.

Table 1 - Objectives (*Obj.*), Requirements (*Req.*), and Evaluation Criteria (*E.C.*) to meet the *usability* need.

6.2.1- GOAL 1: The Design Should be Easy for AFOLs to Use			
Objective	Metric		Justification
	Requirement	Evaluation criteria	
Obj. 1. The design shall be operable without specialist's help.	*Req. 1.* The product shall score >1.08 on the perspicuity of the product, as laid out in the User Experience Handbook [30].	*E.C. 1.* The higher the perspicuity score, the better.	AFOLs should be able to use the machine without needing a specialist because users prefer designs that are easy to use [28] (Appendix D, Figure 1) and high success rates for first-time users of a product is crucial for evaluating its usability [29] (Appendix D, Figure 2). To ensure the design can easily be understood, we aim for a perspicuity score above 1.08, as defined in the User Experience Handbook, which would show that the design performs "above average" in terms of ease of learning of using the product [30] (Appendix E, Figure 1).
Obj. 2. The design shall be lightweight.	*Req. 2.* The product shall weigh less than 23 kg.	*E.C. 2.* The lower the NIOSH Lifting equation (Appendix E, Figure 3), the better.	As stated in [28, 29], a design is more usable when it is easier for users to handle. ToroLUG members have stated that a lightweight product would increase their ease of use (Appendix B, Figure 6). For safe handling, the NIOSH Lifting Equation recommends a maximum weight of 23 kg for objects requiring manual lifting, ensuring suitability for most users [31] (Appendix E, Figure 2).
Obj. 3. The design shall be compact enough to fit within standard tabletop dimensions.	*Req. 3.* The product's dimensions shall be contained within 36 inches (width), 68 inches (length), and 29 inches (height).	*E.C. 3.* The smaller the size, the better.	As stated in [28, 29], a design is more usable when it is easier for users to handle. ToroLUG members note that a smaller, table-top-sized device would be most convenient to use. (Appendix B, Figures 7 and 8). Based on data from World Interiors, the largest recommended dimensions for a table-top LEGO sorter, following standard furniture sizes, should be 36x68x29 inches [32] (Appendix E, Figure 4).

Obj. 4. The design shall sort LEGOs automatically.	*Req. 4.* The system shall operate independently without requiring the user's help during sorting.		To improve usability, human effort should be minimized [33] (Appendix D, Figure 3). Members expressed a preference for a hands-off system, given it would sort "properly" and "safely" (Appendix B, Figure 9). Thus, the LEGO sorter should include an automated sorting system, as outlined in [34] (Appendix C, Figure 16).
Obj. 5. The design shall keep the LEGOs dust and dirt-free.	*Req. 5.* The product shall utilize a MERV parameter of 4-8 for filtration.		As noted in [33], minimizing the amount of human effort expended increases usability. A mechanism for separating LEGO bricks from dust and dirt would decrease the human effort of ToroLUG users, a feature which they have claimed would help them (Appendix B, Figure 10). According to MERV standards, a MERV value of 4-8 is effective for filtering dust and dirt in homes and commercial buildings [35] (Appendix E, Figure 5).
Obj. 6. The design shall sort LEGO bricks listed in "Most Common LEGO Parts", into at least one category, between colour, element, or size [7].	*Req. 6.1* If more than one characteristic is employed, different modes shall be incorporated to allow for choice of separation method.	*E.C. 6.* The more options to sort by, the better.	A product's design should enable users to achieve their goals effectively and with satisfaction [33] (Appendix D, Figure 4). Because ToroLUG members note that LEGO users have different "philosophies" on sorting parts (Appendix B, Figure 11), we will avoid enforcing any specific feature and consider multiple characteristics during sorting.
	Req. 6.2. The product shall sort LEGOs into an "Other" section,		By sorting through the most common LEGO bricks, there will be bricks that won't be recognized by the sorter. According to a survey by LEGO Architect, most LEGO users have LEGO pieces that are elements, rather than set pieces [36] (Appendix C, Figure 17). Additionally, former LEGO ambassador David

	where it can store unidentified LEGO products.		Eaton reports that 10-15 adult-targeted sets are released annually, introducing new parts that may differ from standard bricks [37] (Appendix C, Figure 18). Set-specific pieces may have irregular shapes that may interfere with sorting processes. As well, they may require the sorting device may need to undergo regular changes, which may become frustrating for ToroLUG users who own older versions. Therefore, uncommon pieces can be sorted into an 'other' section for users to handle separately.
Obj. 7. The levels of specificity of sorting shall be chosen by the user.	*Req. 7.* There shall be at least 4 levels of specificity within sorting.	*E.C. 7.* The more levels of specificity available, the better.	As noted in [33], a product's design should enable users to achieve their goals effectively and with satisfaction. Reviews of previous designs, such as LEGO Sort and Store (see Section 7.1), highlight dissatisfaction with the limited range of sorting specificity, and ToroLUG members expressed frustration with similar-sized bricks being grouped together using this device (Appendix B, Figure 1). Given the diverse preferences of stakeholders, we will not enforce a specific number of sorting levels. However, ToroLUG members have indicated a preference for at least 4 sorting layers (Appendix B, Figure 12).

Table 2 - Objectives (*Obj.*), Requirements (*Req.*), and Evaluation Criteria (*E.C.*) to meet the *reliability* need**.**

6.2.2- GOAL 2: The Design Shall be Optimized to Perform Reliably			
Objective	Metric		Justification
	Requirement	Evaluation criteria	
Obj. 8. The design shall sort through the	*Req. 8.* The cycle time, as defined by the Guide	*E.C. 8.* The lower the cycle time, the	User time is considered an "expendable" resource [33] (Appendix D, Figure 5), so minimizing time spent on sorting is key to improving usability. ToroLUG

LEGOs with a cycle time equivalent to industry sorting standards.	to Operational Technology, shall be at most 4 seconds [39] (Appendix E, Figure 6).	better.	members also report that most of their time is spent sorting, which they would rather spend building (Appendix B, Figure 4). To ensure the design is reliable in its quick performance, of quickly sorting through LEGO bricks, we set the operational constraint to be time taken per LEGO brick, as per the definition of reliability in Appendix D, Figure 6 [40]. Extrapolating data from industrial fruit sorters, which take about 3 seconds per item, and based on feedback from ToroLUG members, the preferred cycle time for LEGO sorting is around 4 seconds per piece [41] (Appendix C, Figure 20; Appendix B, Figure 13).
Obj. 9. The design must withstand continuous use without failure. Here, failure refers to not being able to sort within the determined accuracy, as per its MTBF score.	*Req. 9.* The product's MTBF, as defined in Reliability Analysis in Fundamentals of Electronic Systems Design, shall be approximately 38.75 [42] (Appendix C, Figure 21).	*E.C. 9.* The higher the MTBF rating, the better.	To ensure the design is reliable, meaning it will perform its intended function under specified conditions [40] (Appendix D, Figure 7), we must ensure the LEGO sorter can handle dense plastic bricks. Stakeholders also agree that the device should be durable enough for LEGO sorting (Appendix B, Figure 14). Based on data from existing machinery's MTBF [42], if the LEGO sorter uses one of the mentioned mechanisms, it is expected to meet or exceed the MTBF of the lowest-performing mechanism, 38.75 for a "winder" [43] (Appendix C, Figure 22).
Obj. 10. The design shall consistently sort pieces, as listed within "Most	*Req. 10.* The system shall have at least an 80% accuracy when sorting LEGOs.	*E.C. 10.* The higher the accuracy, the better.	To increase the reliability of the design, measured by the frequency of failures over a given time period [40] (Appendix D, Figure 8), we must reduce failures, such as missorted LEGOs. One ToroLUG member shared a negative experience with the LEGO Sort and Store (Section 7.1), where overlapping bricks hindered sorting efficiency

Common LEGO Parts", correctly, [7].			(Appendix B, Figure 1). Therefore, the sorter must handle multiple sizes of LEGO bricks simultaneously. Based on AI model data, we expect an accuracy of around 80% in identifying common LEGO bricks [44], [7] (Appendix C, Figure 23).

Table 3 - Objectives (*Obj.*) and Requirements (*Req.*) to meet the *safety* need.

6.2.3- GOAL 3: The Design Shall be Safe to Use		
Objective	Metric Requirement	Justification
Obj. 11. The design shall not have exposed moving parts	*Req. 11.* The product must abide by ISO 13857:15, for each opening on the device [45].	Safety risks arise from users' decreased awareness [40] (Appendix D, Figure 9), and exposed moving parts can pose hazards if fingers, hands, or nearby objects get caught, potentially causing injury or damage. To mitigate this risk, all moving parts should be enclosed, preventing pinch points. This is particularly important since the tool may be used near children, who may have less awareness of potential hazards. To ensure safety, the device should adhere to ISO 13857:15, which defines safety distances to prevent harm from upper and lower limbs [45] (Appendix E, Figure 7).
Obj. 12. The design shall not have sharp edges.	*Req. 12.* The product must pass the UL 1439 sharp edge test [46].	As stated above, potential safety issues for a device can come from decreased awareness of the user [40]. Having sharp edges reduces the risk of harm to the user during use and during the transport of the tool.
Obj. 13. The design shall have a	*Req. 13.1.* If the system includes automatically moving parts,	A safety case should be integrated into every system to ensure its relative safety [40] (Appendix D, Figure 10) – thus, the LEGO sorter automatically shutting off is this 'safety case' that ensures the user and LEGOs remain safe, and the tool remains usable after rectifying the

shutoff feature in case of malfunction	the system must include a lockout feature where, in case of malfunction, it can shut itself off, as per CSA Z460-20 [47].	malfunction. Therefore, there should be a safety system that automatically responds to malfunctions, like an automatic shut-off [40] (Appendix D, Figure 11). Potential malfunctions could include a piece becoming lodged in the mechanics or a non-LEGO object being involved in the sorting process. This would align with the “lockout” definition in CSA Z460-20 [47] (Appendix E, Figure 8).
	Req. 13.2. The product must present an automatic shut-off feature as an option to the user, lest the user need to manually shut off the machine.	Following the justification above, the incorporation of an emergency stop would be beneficial since it ensures the safety of operation, allowing users to have the choice of shutting the machine when incidents external to the machine occur. If there is an emergency, this feature must shut off all operations and moving parts as per ISO 13850 [48] (Appendix E, Figure 9).

7. Reference Designs

This section examines the strengths and weaknesses of existing LEGO sorting solutions, both commercial products and prototypes, to identify areas for improvement.

7.1. Official LEGO Sort & Store

The LEGO *Sort & Store* is an official LEGO product made to help children sort batches of LEGO [49] (Figure 8). It comprises 3 levels with 2 filters (shown in Figure 9), to sort different sizes of LEGO blocks.

Figure 8 - The official LEGO Sort and Store product. [49]

This design falls short of the expectations of ToroLUG members in terms of accuracy, specificity, and performance. Though unquantified, multiple ToroLUG members and other LEGO users mention that bricks of vastly different sizes are sorted into the same category (Appendix B, Figure 1), and that the "large" and "small" filters have minimal difference [38] (Appendix C, Figure 24; Figure 9). This decreases the accuracy of sorting (*Req. 10)*. Furthermore, ToroLUG members claim they build MOCs "more sophisticated and less general than what a child might build" (Appendix B, Figure 16), with much more specific brick types. The Sort & Store's sorting is much more generic than required, with only two levels rather than the minimum of four, failing to meet *Req. 7.* for different specificities Lastly, small pieces often get stuck in the holes [50] (Appendix C, Figure 25), obstructing other pieces, hindering sorting overall. In *Req. 9*, this may cause lower MTBF scores.

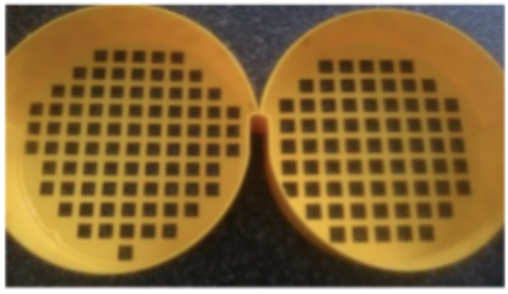

Figure 9 - Picture of the filter levels of the LEGO Sort and Store product where the differences between small and big gaps are not significant [38].

Overall, the LEGO sorting head is not accurate, specific, or reliable enough to meet the AFOLs' needs.

7.2. AI LEGO Sorter

This sorting device is a project of an AFOL, an unofficial product that was made for their own use, and performs well in accuracy and categorization. The design is 90% accurate, exceeding the accuracy requirement of 80% from *Req. 10*. It sorts 18 features, surpassing *Req. 7* [51] (Appendix C, Figure 26; Appendix C, Figure 27).

However, from the images published on the project's website shown in Figure 10, the size of the machine is too large for ToroLUG users, and can be potentially unsafe. Through comparison with the size of LEGO bricks and surroundings, and considering that the setup of the software required for the machine spans another table itself, this design exceeds tabletop dimensions, failing to meet *Req. 3*. Additionally, the design's construction using heavy materials like wood and metal would suggest a higher weight, which would potentially violate *Req 2.* Lastly, the mechanism itself has exposed, moving parts, such as

the conveyor belt that is used to transport the LEGO (white strip on the bottom of the right image of Figure 10), which could pose a hazard to users, as per *Req. 11*.

Figure 10 - Picture of the AI LEGO sorter. By comparison with the LEGO pieces and the surroundings, it can be concluded that the stakeholders' requirement of a table-top size (*Req 3)* is not met [51].

Despite its impressive sorting accuracy and feature capacity, this AFOL's sorting device ultimately falls short of practical application for ToroLUG members due to its excessive size, potentially unsafe design, and likely non-compliant weight.

7.3. ZF700 GroTech Laser sorter

The laser sorting machine ZF700 by GroTech in Figure 11 uses lasers to sort materials based on colour, structure, and shape-which aligns closely with the needs of a LEGO sorter. Its ability to adjust sorting parameters to differentiate materials to a high specificity may be adapted to sort bricks by types and size [52] (Appendix C, Figure 28).

The machine surpasses our requirements in accuracy and cycle time. With a sorting accuracy exceeding 99.9% (Appendix C, Figure 29), meeting the accuracy requirement of *Req. 10*. Its median throughput of 5 tons per hour (Appendix C, Figure 30) corresponds to a cycle time of approximately 1.38 seconds per LEGO piece, outperforming the required cycle time of 3.7 seconds per brick (*Req. 8*).

However, the machine weighs 1665 kg and measures 3030 mm x 1658 mm x 1850 mm. It is not a small or lightweight design (Appendix C, Figure 29), failing *Req. 2* and *Req.3*.

Figure 11 - The laser Sorting Machine ZF700 by GroTech [52].

Though this solution is too large to be viable, its underlying technology offers valuable insight into sorting algorithms that may be adapted to the solution. This insight must be modified to suit a smaller, more compact design.

8. Conclusion

In conclusion, sorting LEGO bricks is a time and labour-intensive task that hinders creativity and building in the ToroLUG community. Research and community outreach shows that an automated brick sorting machine may improve this obstacle. The design must accurately and safely sort LEGO pieces into specific categories in a short time, while being compact and table-top-sized - something current designs fail to do. The requirements open up a clear design space, presenting the framework to develop a usable, reliable, and safe design that will allow stakeholders to spend less time sorting, and more time embracing their creativity.

9. References

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10. Appendices

10.1. Appendix A: Excerpts from the ToroLUG Official Discord Server

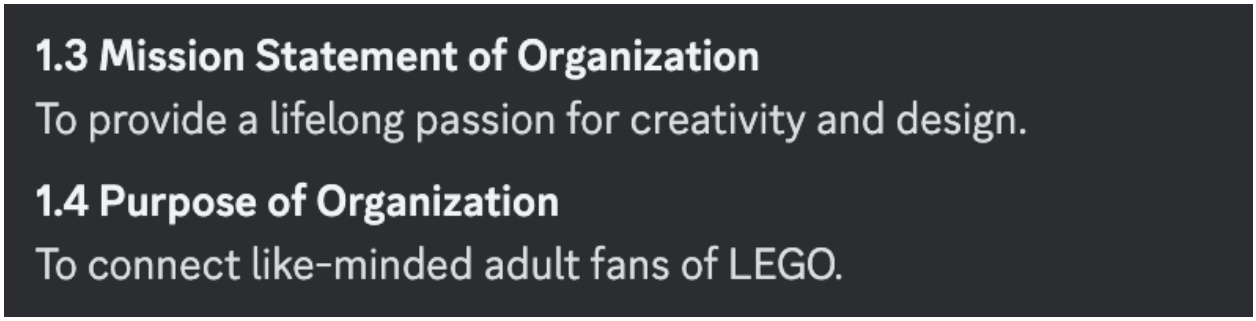


Figure 1 - Screenshots of the *Overview of Organization* section (1.0) of the ToroLUG by-laws, as taken from their Discord channel. Specifically, the mission statement (1.3) and purpose of organization (1.4) are outlined.

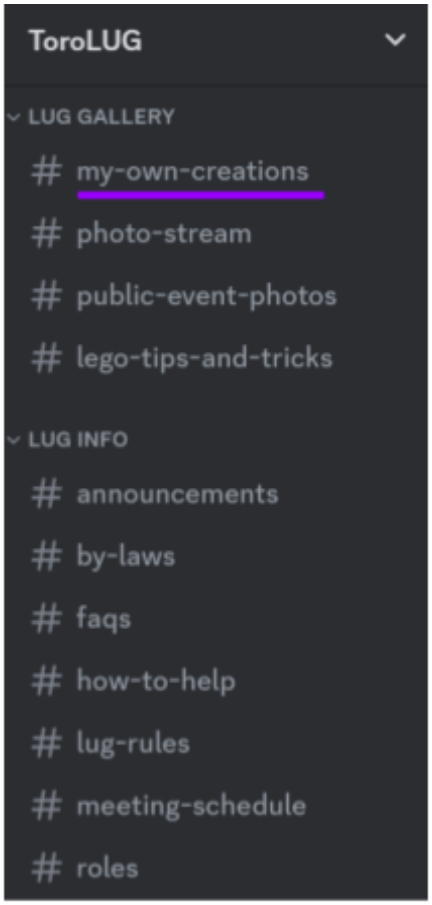
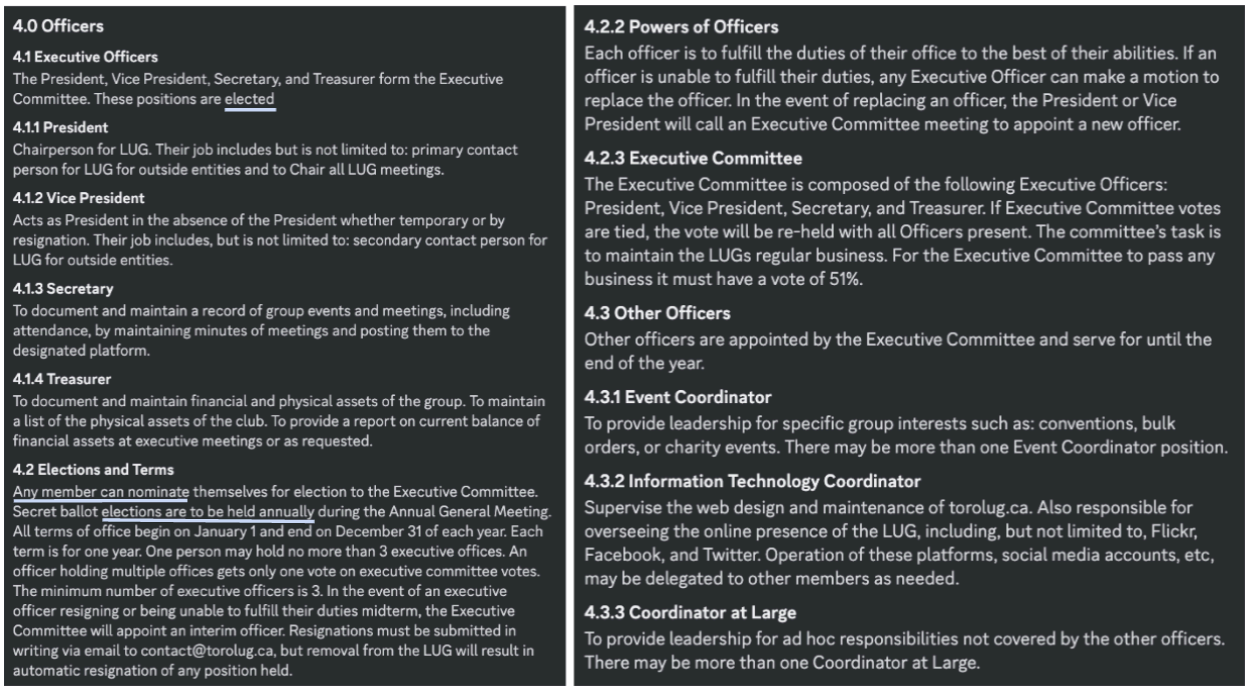


Figure 2 - Screenshot of the Discord channels in the ToroLUG server, featuring the my-own-creations channel, among others.



4.0 Officers

4.1 Executive Officers
The President, Vice President, Secretary, and Treasurer form the Executive Committee. These positions are elected

4.1.1 President
Chairperson for LUG. Their job includes but is not limited to: primary contact person for LUG for outside entities and to Chair all LUG meetings.

4.1.2 Vice President
Acts as President in the absence of the President whether temporary or by resignation. Their job includes, but is not limited to: secondary contact person for LUG for outside entities.

4.1.3 Secretary
To document and maintain a record of group events and meetings, including attendance, by maintaining minutes of meetings and posting them to the designated platform.

4.1.4 Treasurer
To document and maintain financial and physical assets of the group. To maintain a list of the physical assets of the club. To provide a report on current balance of financial assets at executive meetings or as requested.

4.2 Elections and Terms
Any member can nominate themselves for election to the Executive Committee. Secret ballot elections are to be held annually during the Annual General Meeting. All terms of office begin on January 1 and end on December 31 of each year. Each term is for one year. One person may hold no more than 3 executive offices. An officer holding multiple offices gets only one vote on executive committee votes. The minimum number of executive officers is 3. In the event of an executive officer resigning or being unable to fulfill their duties midterm, the Executive Committee will appoint an interim officer. Resignations must be submitted in writing via email to contact@torolug.ca, but removal from the LUG will result in automatic resignation of any position held.

4.2.2 Powers of Officers
Each officer is to fulfill the duties of their office to the best of their abilities. If an officer is unable to fulfill their duties, any Executive Officer can make a motion to replace the officer. In the event of replacing an officer, the President or Vice President will call an Executive Committee meeting to appoint a new officer.

4.2.3 Executive Committee
The Executive Committee is composed of the following Executive Officers: President, Vice President, Secretary, and Treasurer. If Executive Committee votes are tied, the vote will be re-held with all Officers present. The committee's task is to maintain the LUGs regular business. For the Executive Committee to pass any business it must have a vote of 51%.

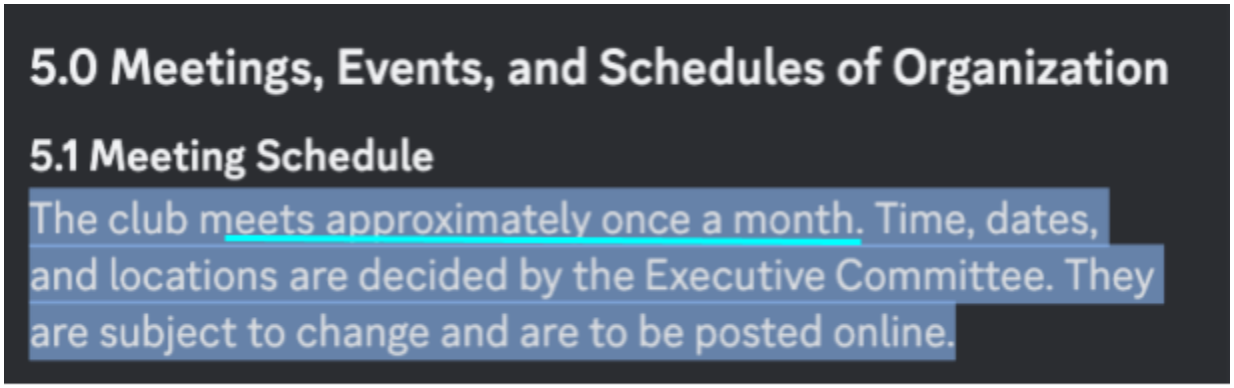
4.3 Other Officers
Other officers are appointed by the Executive Committee and serve for until the end of the year.

4.3.1 Event Coordinator
To provide leadership for specific group interests such as: conventions, bulk orders, or charity events. There may be more than one Event Coordinator position.

4.3.2 Information Technology Coordinator
Supervise the web design and maintenance of torolug.ca. Also responsible for overseeing the online presence of the LUG, including, but not limited to, Flickr, Facebook, and Twitter. Operation of these platforms, social media accounts, etc, may be delegated to other members as needed.

4.3.3 Coordinator at Large
To provide leadership for ad hoc responsibilities not covered by the other officers. There may be more than one Coordinator at Large.

Figure 3 - Screenshots of the *Officers* section (4.0) of the ToroLUG by-laws, as taken from their Discord channel. Notably, the elections and terms section (4.2) is mentioned in the text, which discusses nominations and voting procedures within ToroLUG for executive positions. Information that is most relevant to what is mentioned in the text is underlined.



5.0 Meetings, Events, and Schedules of Organization

5.1 Meeting Schedule

The club meets approximately once a month. Time, dates, and locations are decided by the Executive Committee. They are subject to change and are to be posted online.

Figure 4 - Screenshots of the *Meetings* section (5.0) of the ToroLUG by-laws, as taken from their Discord channel. Notably, the meeting schedule section (5.1) is mentioned in the text, which discusses ToroLUG's monthly meetings, as highlighted in the image. Information that is most relevant to what is mentioned in the text is underlined.

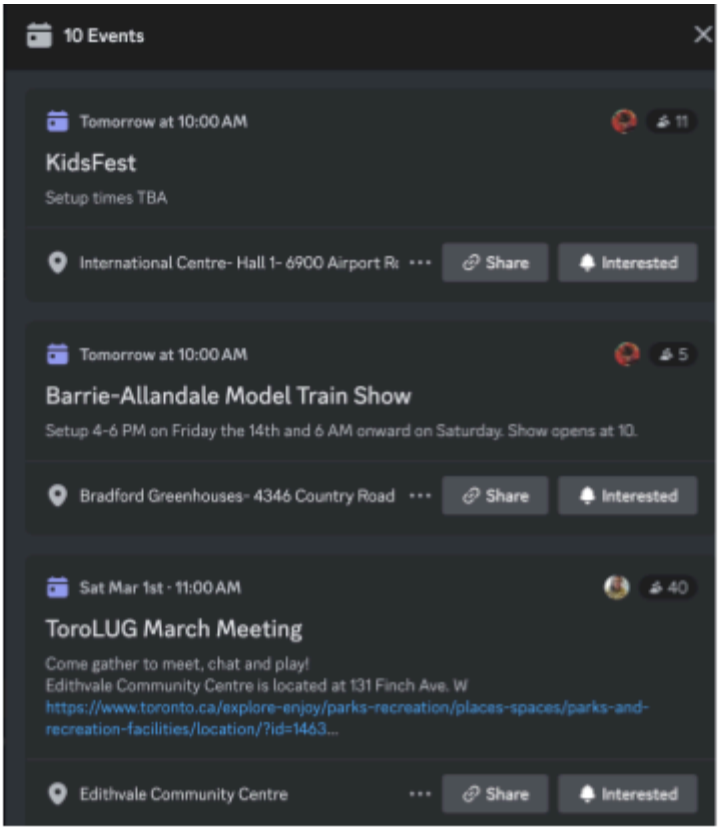


Figure 5 - Screenshots of the *Events* section of the ToroLUG server, as taken from their Discord channel. Notably, the in-person meetings are mentioned in the text, which are shown through the posted dates on their discord channel.

10.2. Appendix B: ToroLUG Survey Feedback and Interactions

I have tried various tools to help with sorting and so far almost all fail. The multi-level "coin sorter" approach doesn't work as element profiles overlap. For example, a 2x2 brick is smaller than a 2x10 brick, but both can end up on the same level in the coin sorter as they both have a side profile that's the same (2 studs in this case). Lego themselves marketed such a tool years ago (giant minifig head that coin sorted on the inside. It was a complete failure as it just didn't work. Good luck!

Figure 1 - Google Form response from members of ToroLug sharing their experience with existing sorters, especially the official LEGO sorter.

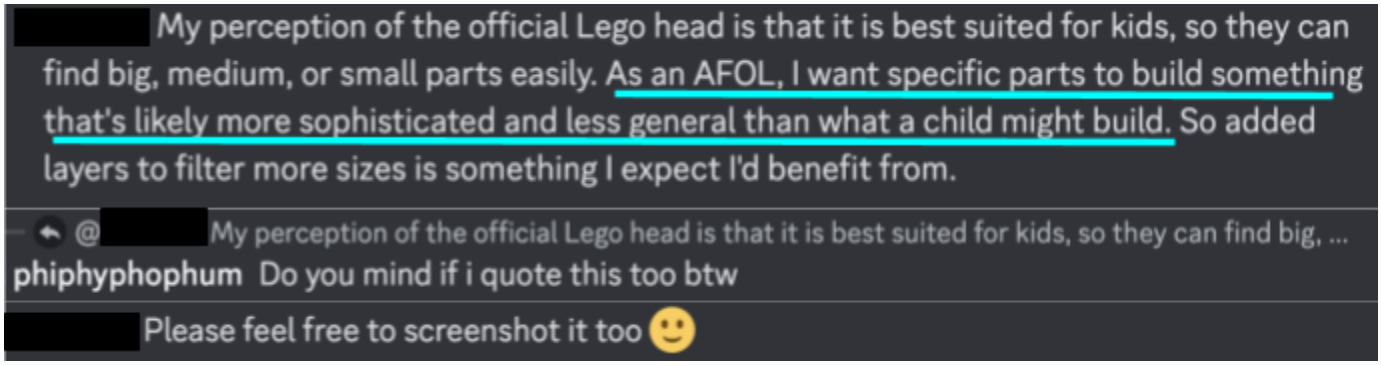


Figure 2 - Screenshot from the chat history with a member of ToroLUG identifying the need for a more sophisticated sorter for AFOLs.

we all have day jobs so there's of variety of schedules to try to plan things. A big challenge is moving large MOCs and the logistics to not screw up the setup and take-downs

Figure 3 - Google Form response from members of ToroLug discussing how their busy schedule prevents them from spending a lot of time on their hobby.

If you break down time spent on the hobby (at least for me), I spend 2/3 of the time sorting and 1/3 of the time building. Something to shift more time to building would be beneficial. I also don't like sorting (some people do, I most def do not) so the task is a necessary evil in order for me to enjoy the hobby. If I don't sort them I won't find what I need which slows down/halts building. Having said all that, there have been many attempts to automate Lego sorting throughout the years and none have been all that successful. LMK if you want more details/examples of what doesn't work.

Figure 4 - Google Form response from members of ToroLug discussing the time-consuming task of sorting.

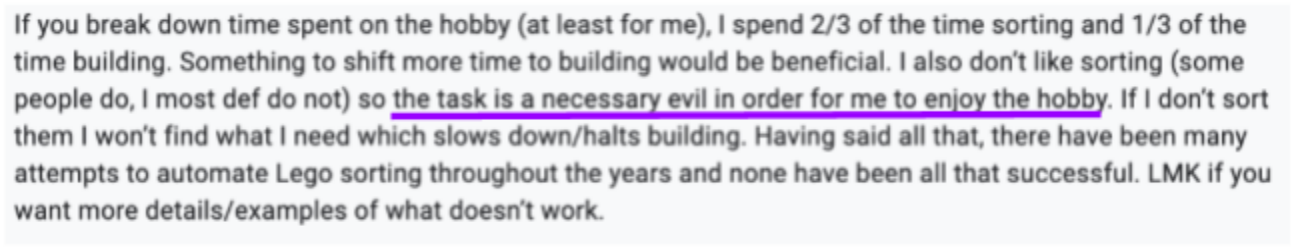


Figure 5 - Google Form response from members of ToroLug discussing how they consider sorting a 'necessary evil' for them to enjoy building LEGO.

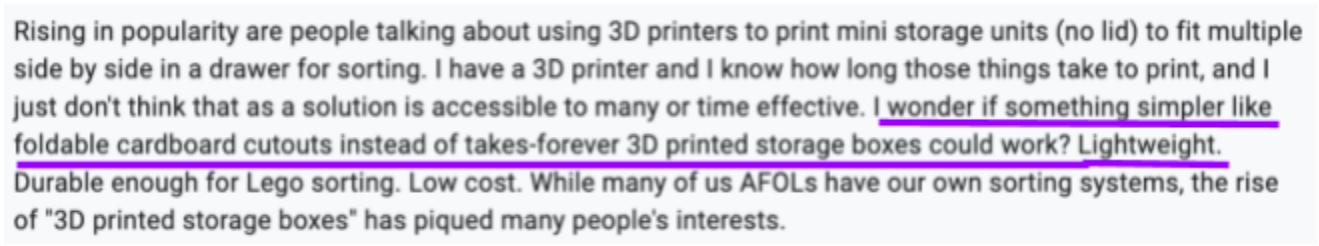


Figure 6 - Google Form response, displaying ToroLUG members' preference to a lightweight design, similar to "foldable cardboard cutouts".

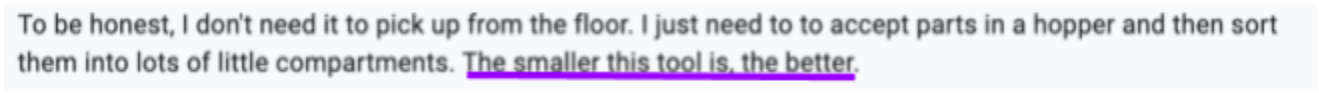


Figure 7 - Google Form response mentioning that the smaller the LEGO sorting tool is, the better.

Figure 8 - Google Form response of ToroLUG member claiming that ideally the device should be table-top sized.

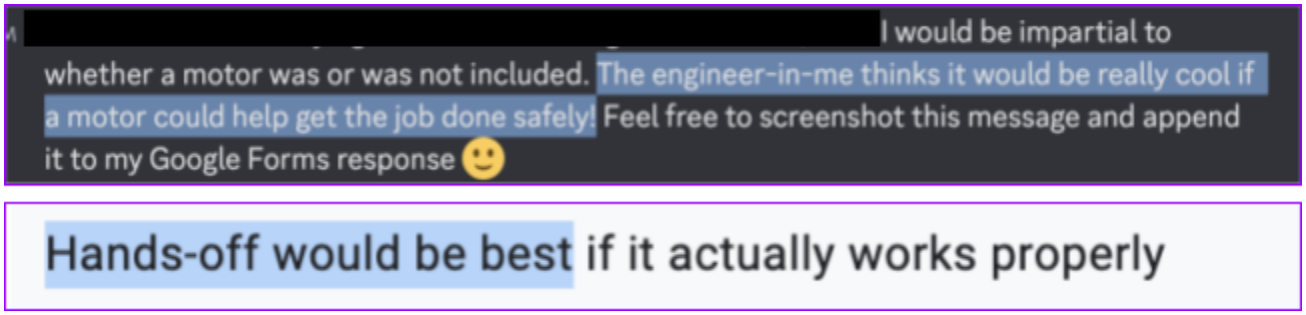


Figure 9 - Direct message history (above) and Google Form response (below), mentioning how an automated system ("motor") or hands-off approach would suit them best, if it "works properly" and "gets the job done safely".

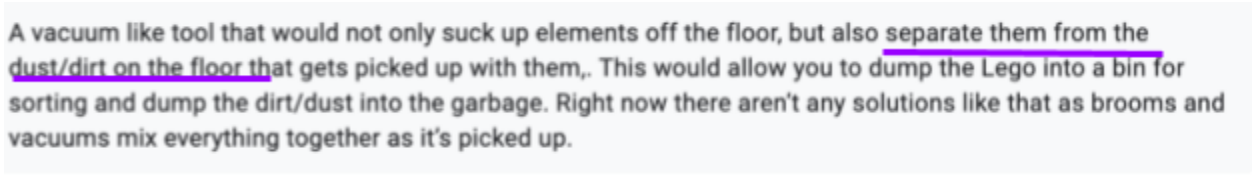


Figure 10 - Google Form response, claiming that they would prefer dust/dirt that can accompany LEGOs during sorted be separated. They claim that solutions right now, like brooms and vacuums, can mix everything together as LEGOs are picked up.

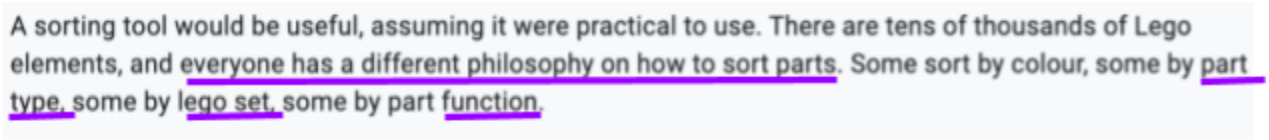


Figure 11 - Google Form response, outlining how every ToroLUG user may have a different philosophy in sorting, and how some may prefer to sort based on parts, sets, or function.

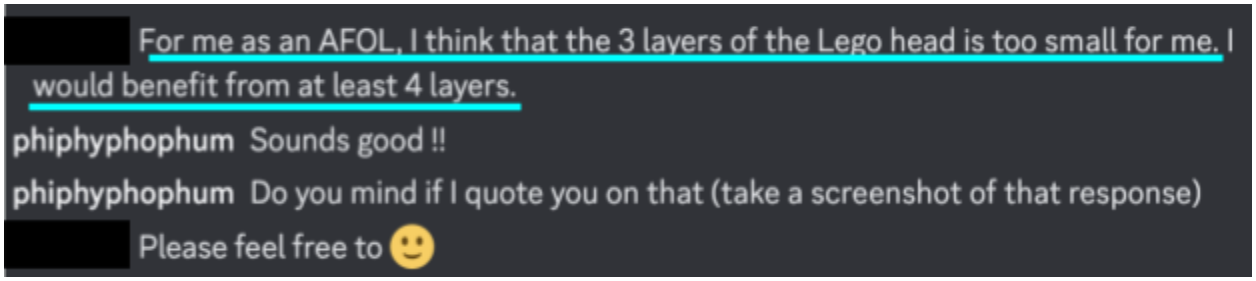


Figure 12 - A ToroLUG member claiming that they are not satisfied with the 3 levels of sorting (referring to the LEGO Sort and Store), and would rather have at least 4 levels of specificity.

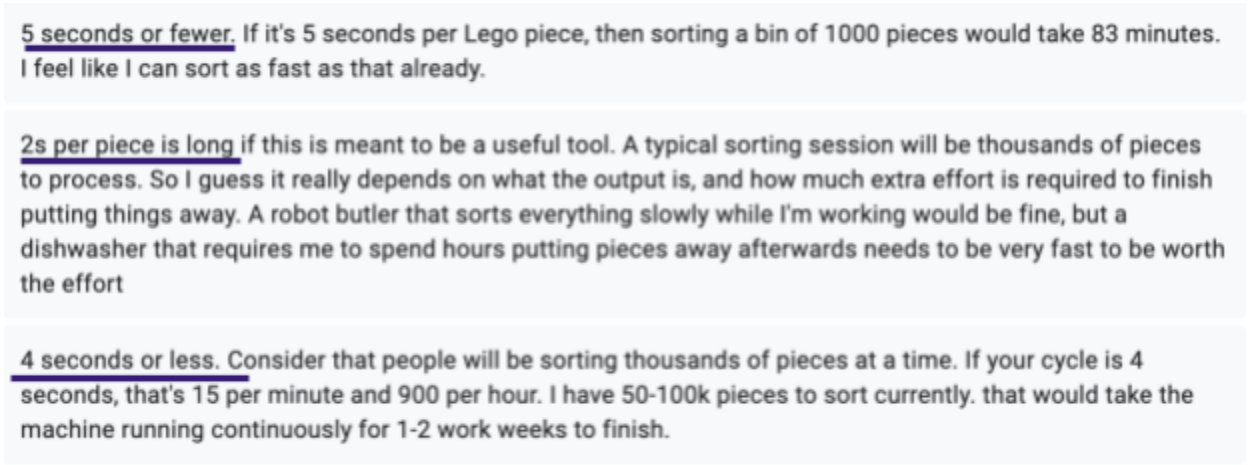


Figure 13 - Three ToroLUG members claiming that 5 seconds, 4 seconds, and 2 seconds or fewer spent on each LEGO brick was preferred, after being told that fruit sorters took around 3 seconds per fruit [41]. An average of around 3.7 seconds was calculated based on all responses.

Rising in popularity are people talking about using 3D printers to print mini storage units (no lid) to fit multiple side by side in a drawer for sorting. I have a 3D printer and I know how long those things take to print, and I just don't think that as a solution is accessible to many or time effective. I wonder if something simpler like foldable cardboard cutouts instead of takes-forever 3D printed storage boxes could work? Lightweight. Durable enough for Lego sorting. Low cost. While many of us AFOLs have our own sorting systems, the rise of "3D printed storage boxes" has piqued many people's interests.

Figure 14 - Google Form response relaying that they would prefer the LEGO sorter be "durable enough for [LEGO] sorting".

A sorting tool would be useful, assuming it were practical to use. There are tens of thousands of Lego elements, and everyone has a different philosophy on how to sort parts. Some sort by colour, some by part type, some by lego set, some by part function.

Figure 15 - Google Form response, highlighting that a sorting tool would be useful to a ToroLUG member, assuming it was practical for them to use.

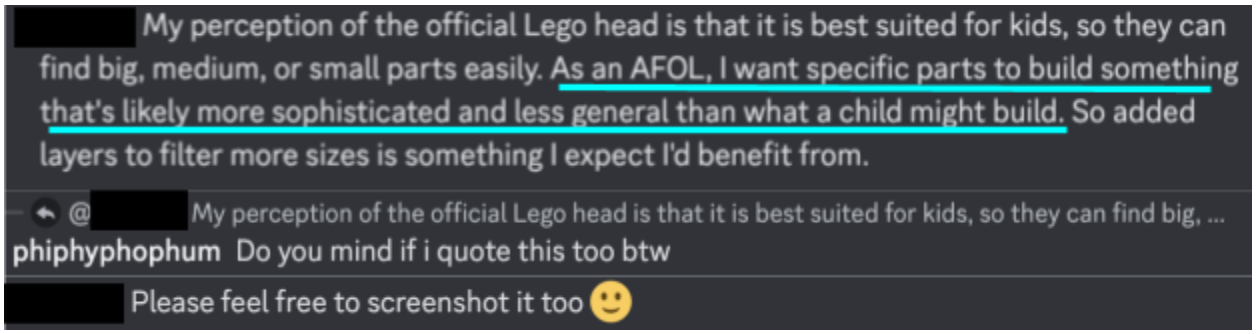


Figure 16 - Direct message conversation with a ToroLUG member, who says that they prefer something "more sophisticated and less general than what a child might build" with the LEGO Sort and Store.

10.3. Appendix C: Source Extracts

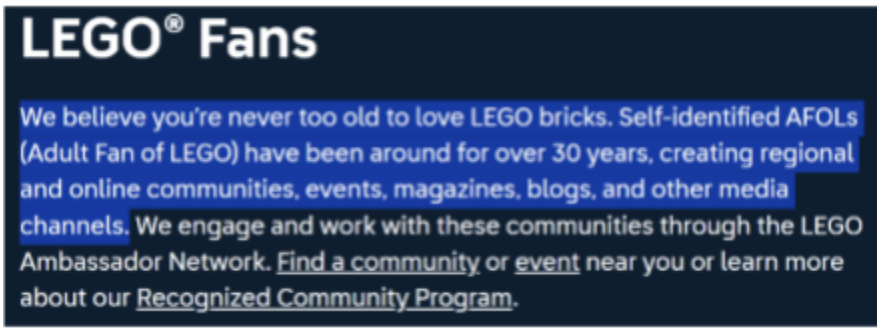


Figure 1 - Screenshot from official LEGO website stating the passion and mission of the community [1].

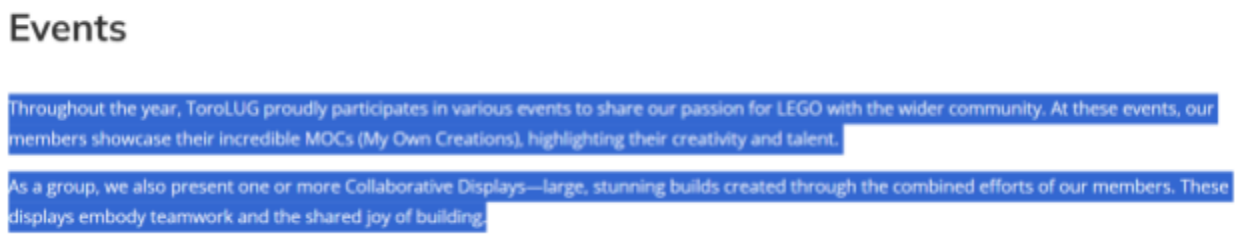


Figure 2 - Screenshot from the ToroLug website introducing the events organized by the community [2].

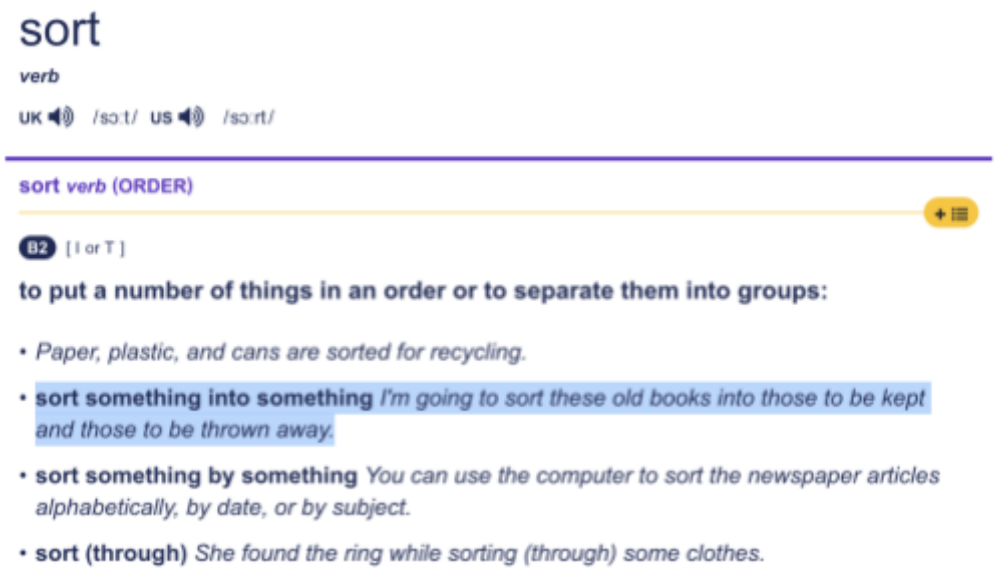


Figure 3 - Screenshot from the Cambridge Dictionary, with the specific definition of "sort something into something" highlighted [6].

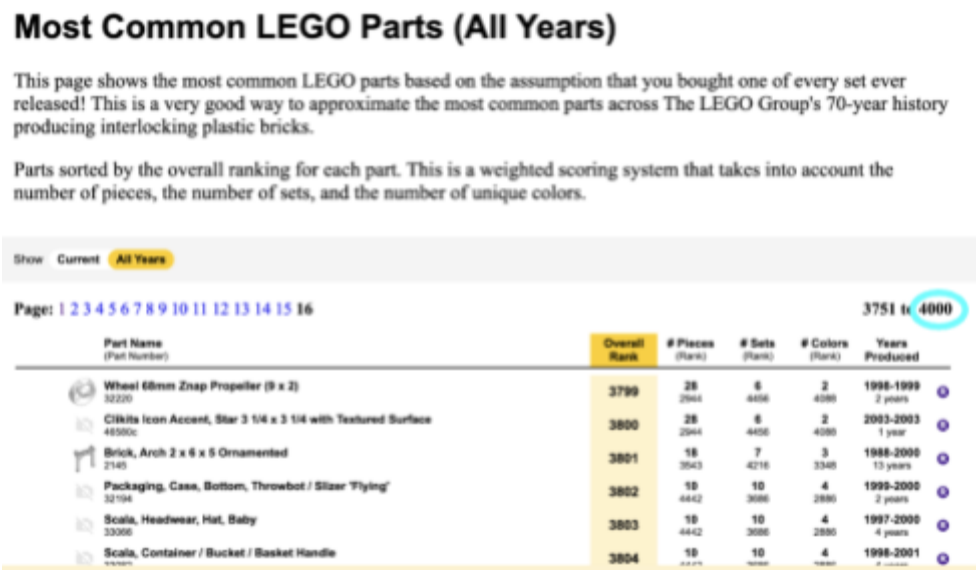


Figure 4 - Screenshot taken from BrickArchitect, outlining the 4000 most common LEGO parts, as circled in blue [7].

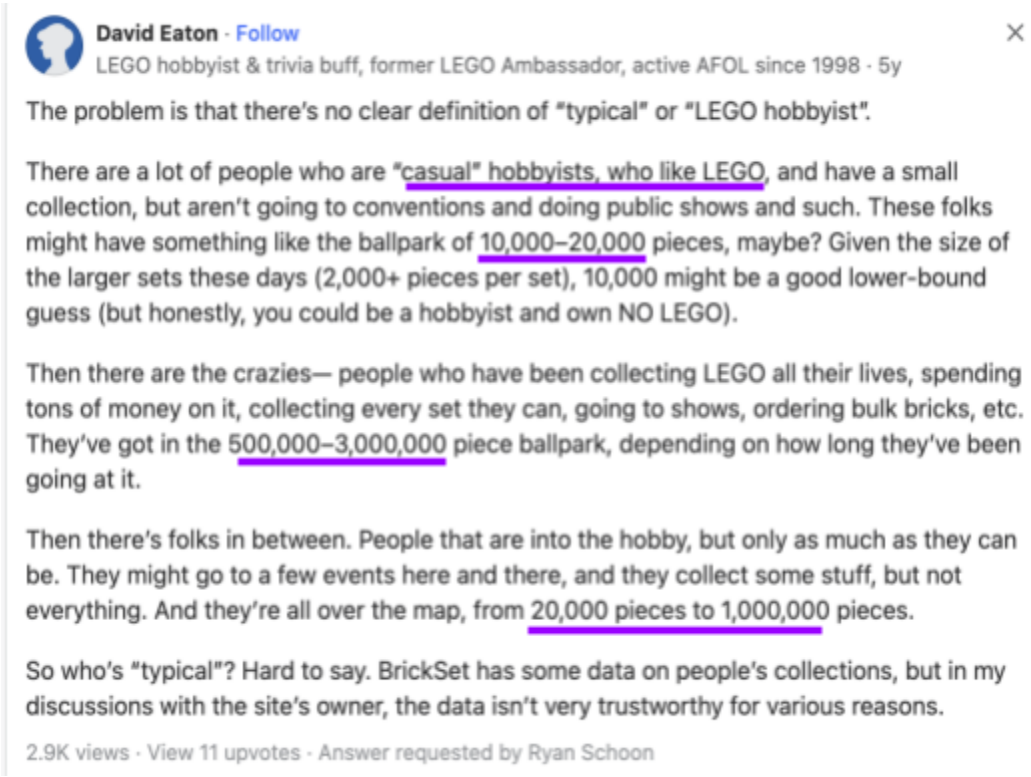


Figure 5 - Screenshot from Reddit where a LEGO hobbyist and former Ambassador talks about the number of lego bricks owned by AFOLs [9].

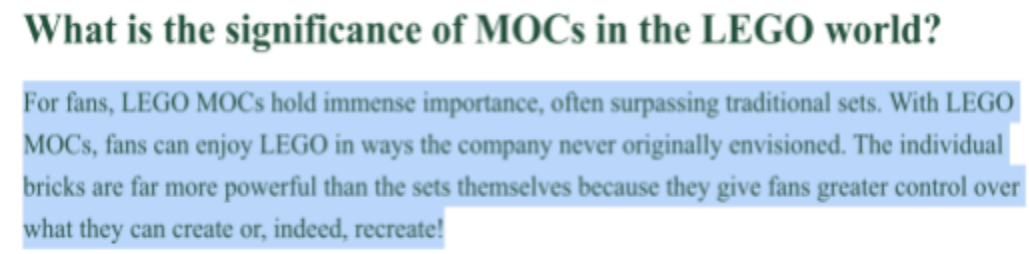


Figure 6 - Screenshot from the website of JMBricklayer, where the importance of MOCs to the LEGO community is discussed [10].

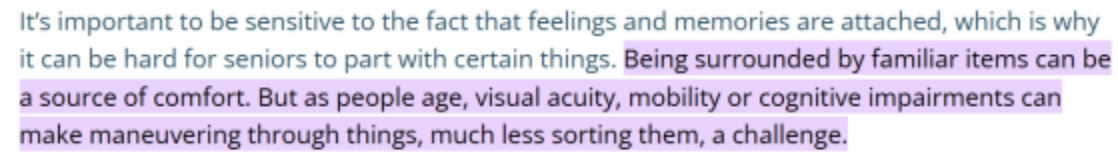


Figure 7 - Screenshot taken from [12], describing that as people age, their mobility can make things like sorting a challenge.

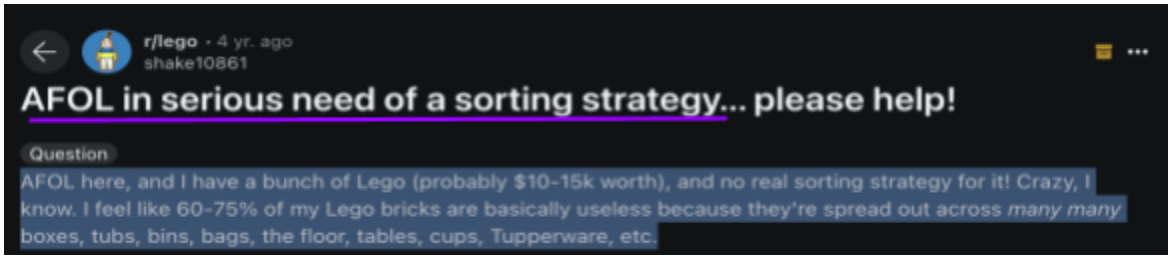


Figure 8 - A screenshot from Reddit where an AFOL identifies their need for a strategy for LEGO sorting [14].

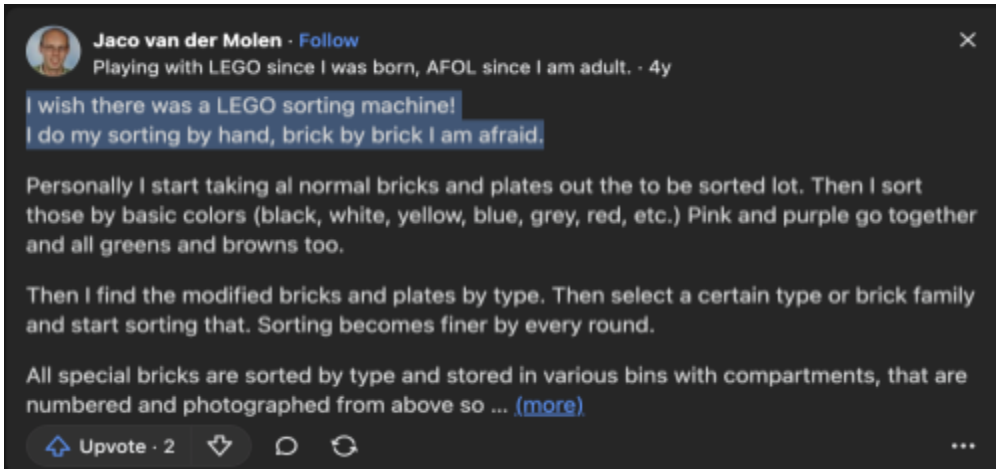


Figure 9 - A post on r/lego, of an AFOL claiming that they "wish there was a LEGO sorting machine" [14].

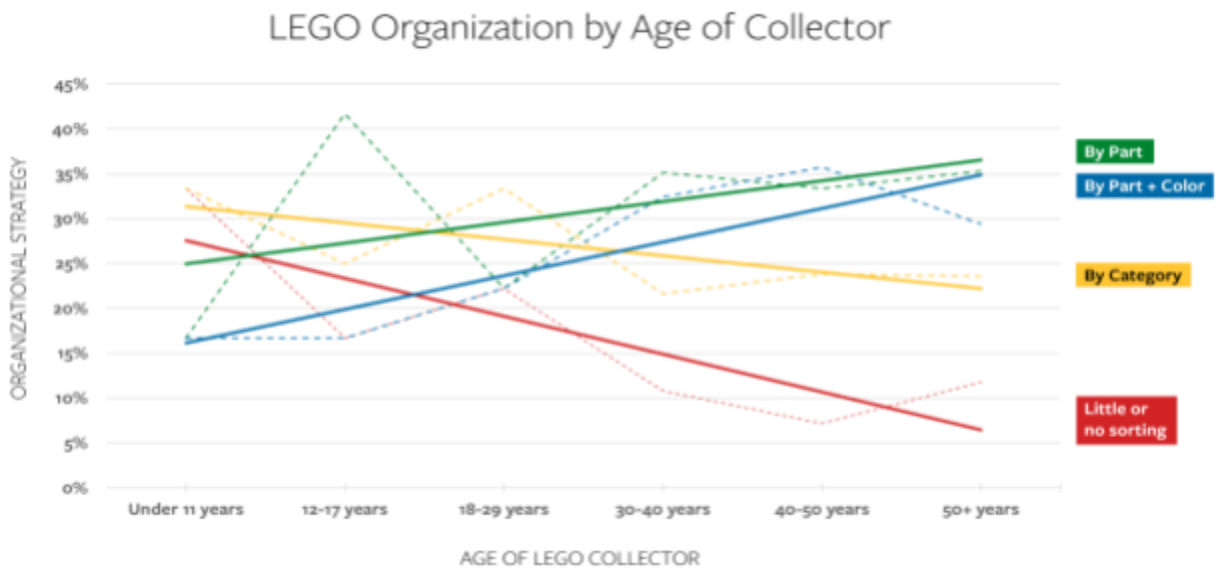


Figure 10 - Statistics for LEGO users' preference for sorting [15].

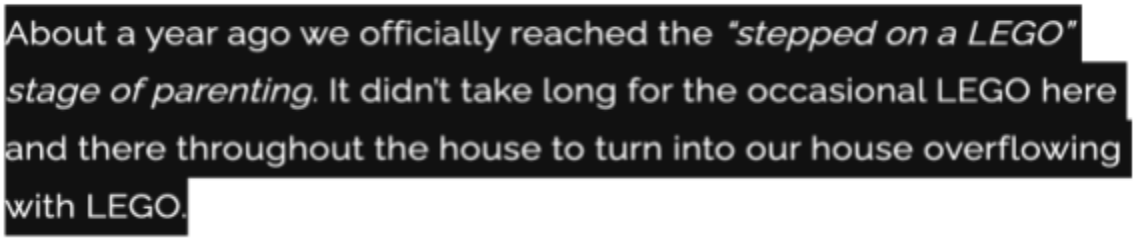


Figure 11 - LEGO in parenting [16].

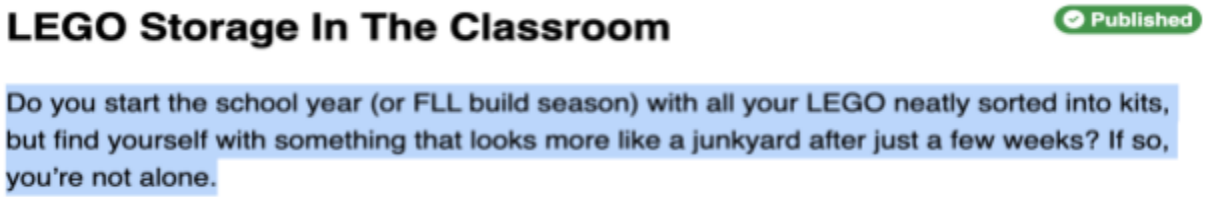


Figure 12 - LEGO in education [18].

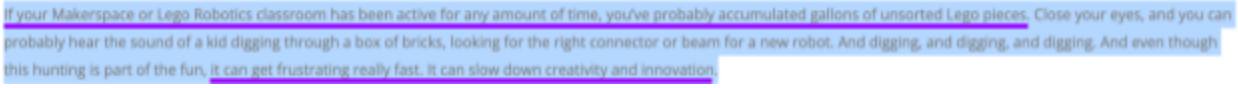


Figure 13 - Cary Busby speaking about how Makerspaces can accumulate gallons of unsorted Lego pieces, which can be frustrating and slow down creativity and innovation [22].

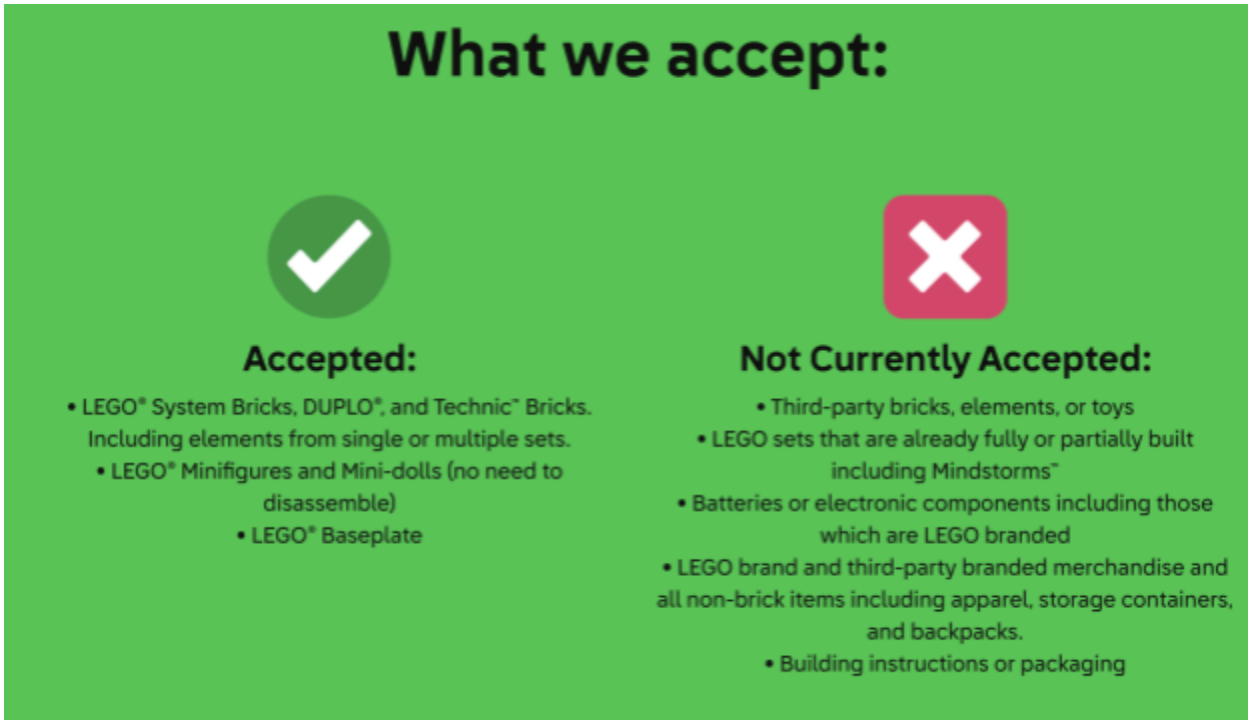


Figure 14 - Screenshot of the LEGO Replay official page, outlining what they do and don't accept [25]. According to their website, they accept any form of donations, as long as they are not built, have no electronics, and do not have third party bricks.

Figure 15 - Screenshot of the ToroLUG "About Us" section, showing that they "celebrate creativity and community through the art of LEGO building" [27].

Automated systems

Mechanised scenery where the power source is not manual, and:scenic motion is directly controlled by an operator at all times (e.g. a chain hoist run from a pendant control), orscenic motion is initiated by an operator, with subsequent control being assumed by a machine (e.g. an automated cue playback system).

Figure 16 - Excerpt taken from the Ontario.ca website, describing what constitutes an "automated system" [34].

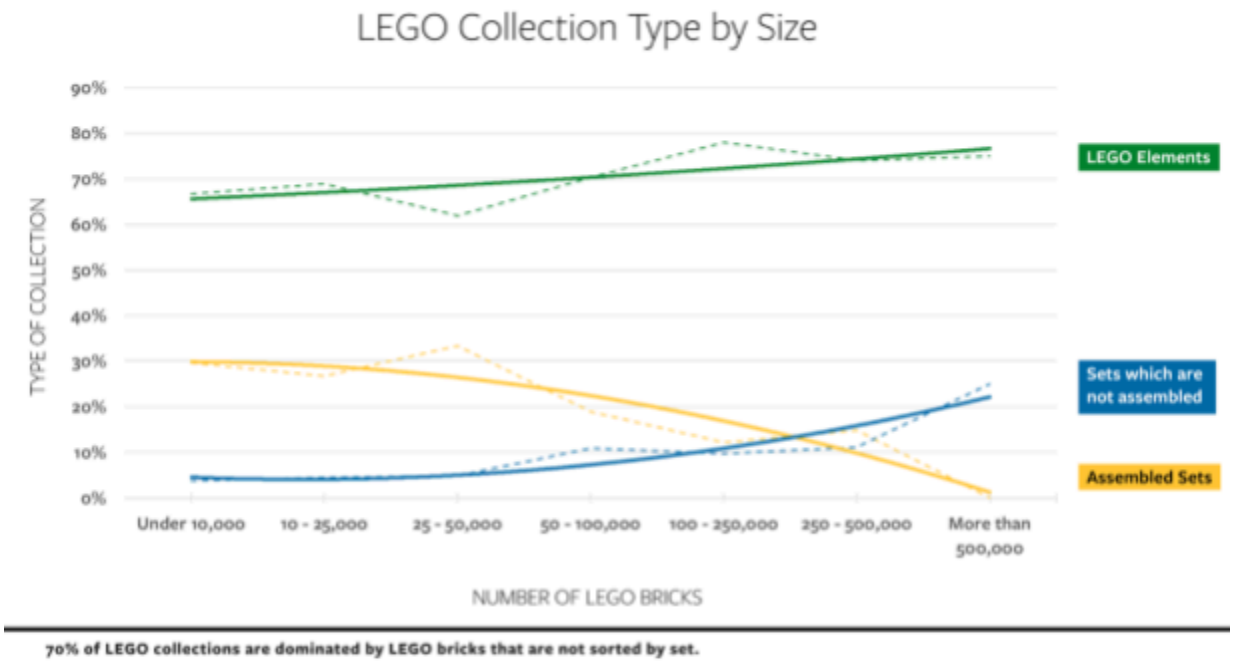


Figure 17 - Screenshot from BrickArchitect, of a graph depicting how most LEGO collections are comprised of individual LEGO elements, rather than set-specific elements [36].

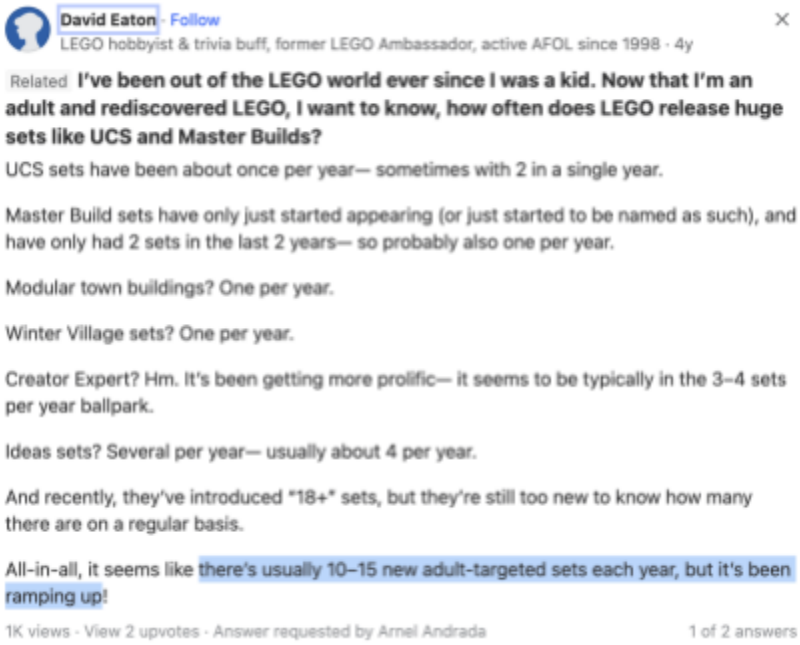


Figure 18 - Screenshot from Quora, of David Eaton's claim about 10-15 new adult-targeted LEGO sets being released each year [37].

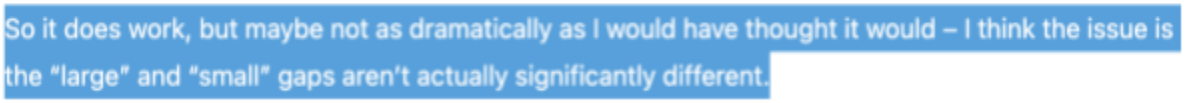


Figure 19 - A screenshot taken from [38], mentioning how there wasn't much distinction between LEGO bricks when sorting for size, using the LEGO Sort and Store.

Tree No	Number of Fruits	Both arms	Puma 560			ABB S4 2.8 robot		
		% of fruits picked	PICK & PLACE Average picking time for system	PICK & PLACE Average picking time for arm	PICK Average picking time for system	PICK & PLACE Average picking time for system	PICK & PLACE Average picking time for arm	PICK Average picking time for system
1	105	100%	3.5 s	2.1 s	1.2 s	2.6 s	5.7 s	4.2 s
2	136	100%	2.9 s	2.6 s	1.2 s	1.5 s	4.4 s	4.1 s
3	117	100%	2.7 s	2.3 s	1.2 s	1.6 s	4.6 s	4.2 s
4	131	100%	2.6 s	2.2 s	1 s	1.5 s	4.6 s	4.2 s
5	147	100%	2.8 s	2.5 s	1.1 s	1.4 s	4.4 s	4.1 s
6	166	100%	2.6 s	2.4 s	0.9 s	1.2 s	4.3 s	4.1 s
7	141	100%	2.5 s	2.3 s	1 s	1.5 s	4.4 s	4.1 s
8	134	100%	3.1 s	2.8 s	1 s	1.7 s	4.6 s	4.2 s
9	102	100%	2.8 s	2.3 s	1.1 s	1.9 s	4.7 s	4.2 s
10	129	100%	3.0 s	2.6 s	1 s	1.6 s	4.5 s	4.1 s
11	124	100%	2.8 s	2.5 s	1 s	1.4 s	4.5 s	4.2 s
12	104	100%	3.2 s	2.8 s	1 s	2 s	4.7 s	4.3 s
13	132	100%	2.9 s	2.5 s	0.9 s	1.8 s	5.0 s	4.6 s
14	139	100%	3.2 s	2.9 s	0.9 s	1.6 s	4.6 s	4.3 s
15	116	100%	3.3 s	2.8 s	0.9 s	1.6 s	4.6 s	4.1 s
16	161	100%	2.9 s	2.6 s	0.8 s	1.6 s	4.5 s	4.2 s
17	146	100%	3.0 s	2.7 s	0.7 s	1.5 s	4.7 s	4.4 s
18	116	100%	2.7 s	2.4 s	1.1 s	1.7 s	7.8 s	4.5 s
19	98	100%	3.4 s	2.9 s	1 s	1.7 s	4.9 s	4.4 s
20	143	100%	2.8 s	2.5 s	0.9 s	1.1 s	4.2 s	4.0 s
21	107	100%	2.8 s	2.4 s	1.2 s	1.6 s	4.6 s	4.2 s
22	55	100%	2.9 s	2.3 s	1.2 s	1.4 s	4.5 s	3.9 s
23	125	100%	2.7 s	2.4 s	1.2 s	1.5 s	4.4 s	4.1 s
24	133	100%	3.3 s	2.9 s	0.8 s	1.7 s	4.8 s	4.4 s
25	142	100%	3.3 s	2.9 s	0.8 s	1.9 s	4.8 s	4.5 s
26	121	100%	2.7 s	2.3 s	1 s	1.9 s	4.7 s	4.3 s
27	129	100%	3.1 s	2.8 s	0.9 s	1.6 s	4.4 s	4.1 s
28	166	100%	3.1 s	2.9 s	0.6 s	1.7 s	4.9 s	4.7 s

Figure 20 - Fruit-sorting data from [41], which yielded around a 3s average for “Pick & Place”.

The *MTBF* (*MTTF*) value can be used as a system reliability parameter or to compare different systems or designs. This value, as we will show later, should only be understood conditionally as the “mean lifetime” (an average value), and not as a quantitative identity between working and failed units. The mean time to failure is

Figure 21 - A screenshot of page 50 of [42] explaining what MTBF (mean time between failure) stands for.

No.	Machine	$MTBF_{\hat{\theta}i}$
1	Winder	38.75
2	Sewing	43.14
3	Twisting	48.71

Figure 22 - listed machinery in [43], along with their associated MTBF.

Model	Top1 accuracy	Top5 accuracy	Epochs run	Training time
VGG16	**92.99%**	**99.00%**	**11**	**04:01:07**
VGG19	91.70%	98.64%	11	04:05:07
ResNet50	**87.40%**	**96.96%**	**14**	**04:04:07**
ResNet101V2	87.20%	96.94%	14	04:10:42
ResNet152V2	86.92%	96.74%	15	04:11:10
ResNet50V2	86.57%	96.72%	14	04:05:15
ResNet152	86.00%	96.28%	13	04:09:27
EfficientNetB1	**84.40%**	**95.85%**	**15**	**04:12:06**
ResNet101	84.09%	95.44%	14	04:16:57
EfficientNetB3	83.58%	95.63%	10	04:14:06
EfficientNetB0	82.87%	95.03%	15	04:15:20
MobileNetV3Large	**82.32%**	**94.80%**	**17**	**04:09:28**
Xception	**82.31%**	**94.95%**	**9**	**04:27:31**
EfficientNetB2	**81.33%**	**94.50%**	**11**	**04:04:16**
InceptionResNetV2	**79.43%**	**93.90%**	**7**	**04:01:10**
MobileNet	78.56%	94.04%	14	04:09:26
DenseNet201	**77.41%**	**92.18%**	**14**	**04:01:57**
MobileNetV2	75.75%	92.29%	16	04:06:31
DenseNet169	75.44%	91.38%	13	04:14:47
DenseNet121	74.01%	90.49%	14	04:06:56
MobileNetV3Small	73.07%	89.97%	17	04:13:45
InceptionV3	71.19%	89.22%	10	04:16:48
EfficientNetB5	66.72%	87.58%	3	04:14:28
EfficientNetB4	65.60%	86.67%	6	04:25:51
NASNetMobile	**59.60%**	**82.08%**	**16**	**04:11:54**
EfficientNetB6	58.34%	82.15%	2	04:35:13
EfficientNetB7	54.38%	78.60%	1	04:03:32
NASNetLarge	53.39%	77.89%	4	04:26:13

Figure 23 - Image taken from page 635 of [44], where the median accuracy of the AI models was taken.

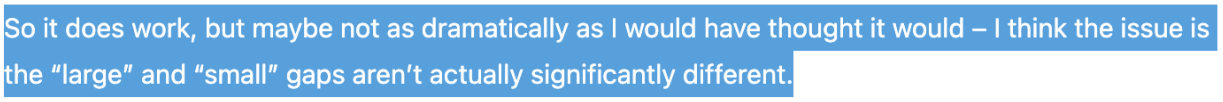


Figure 24 - Screenshot from [38], where the review of the official LEGO sorter describes the product to be less efficient as expected.

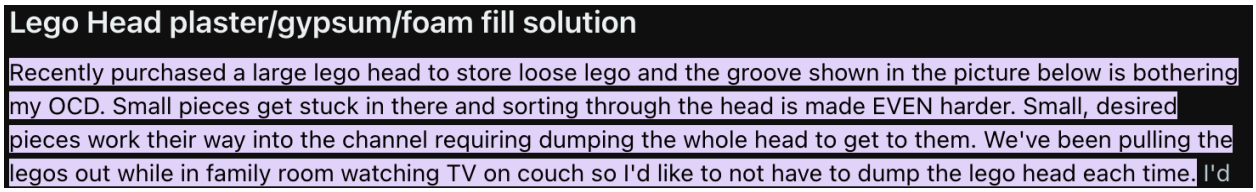


Figure 25 - Screenshot from Reddit [50], where one user discusses the functionality of the official LEGO sorter under the thread of LEGO storage. Specifically, they mentioned that the smaller pieces tend to get stuck and make sorting harder.

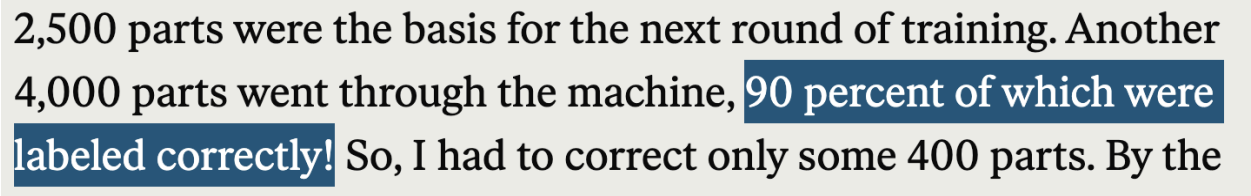


Figure 26 - Screenshot from the website of the AI LEGO Sorter [51], stating that the accuracy of this solution is 90%.

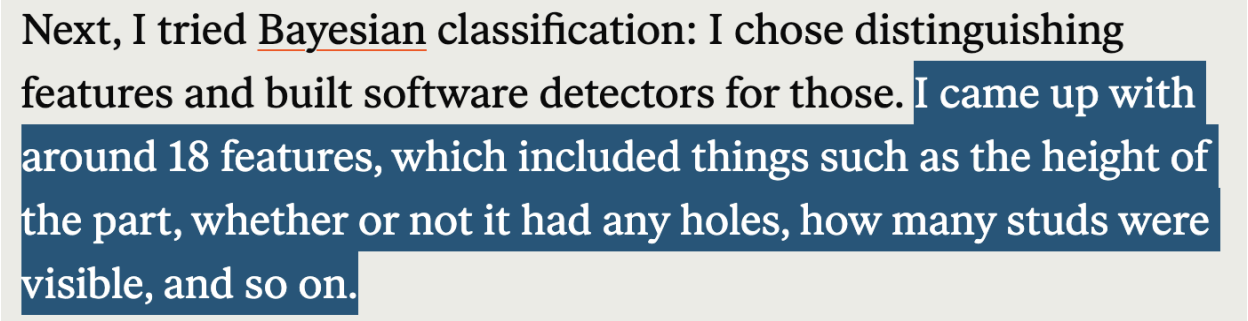


Figure 27 - Screenshot from the website of the AI LEGO Sorter [51], stating that the solution allows for sorting for 18 features.

The laser sorting process offers some more advanced benefits. These sorting units can be modified to handle a variety of different materials on the same line. This capability eliminates the need for recycling centers to install multiple platforms for different materials. In most cases, existing hardware can be converted. There is also no limit to the materials that can be sorted. Everything from paper to iron ore can be separated by a laser process. The flexibility of such a system depends on how the classification is done. The technique judges each item based on its color, structure and shape. Manipulating these variables allows the system to distinguish almost any known material. The evaluated products are then divided into acceptance and rejection flows.

Figure 28 - Screenshot from the website of the GroTech Company [52], introducing the laser sorter. Specifically, it is capable of sorting different objects based on different features.

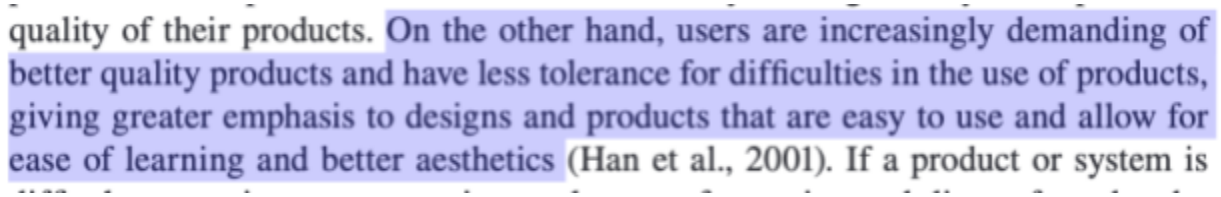
Model	ZF700
Throughput(T/H)	4 - 10
Voltage(V)	110 - 250V(50/60)
Power(KW)	3.5
Sorting accuracy(%)	>99.99
Rjection rate	30:1
Air source pressure (Mpa)	0.6-0.8
Air consumption(m3/min)	<4.5
Weight/(KG)	1665
Dimension(L*W*H/mm)	3030*1658*1850

Figure 29 - Screenshot from the website of the GroTech Company [52], identifying the specifications of the design, including dimensions, accuracy, weight, etc.

Product output(t/h)	3.0-8.0

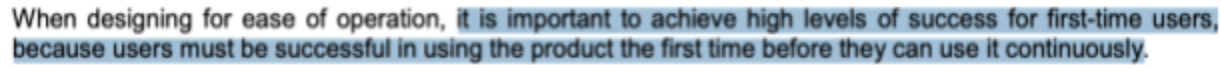
Figure 30 - Screenshot from the website of the GroTech Company [52], where the output of the product is 3-8 tons per hour.

10.4. Appendix D: DfXs



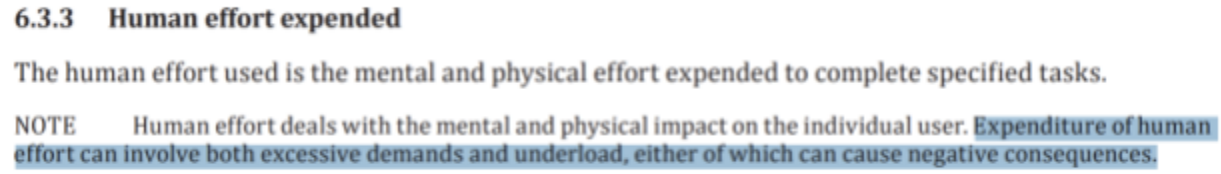
quality of their products. On the other hand, users are increasingly demanding of better quality products and have less tolerance for difficulties in the use of products, giving greater emphasis to designs and products that are easy to use and allow for ease of learning and better aesthetics (Han et al., 2001). If a product or system is

Figure 1 - Excerpt from the handbook for Usability and User Experience, page 3, discussing how users give more emphasis to designs and products that are easier for them to use [28].



When designing for ease of operation, it is important to achieve high levels of success for first-time users, because users must be successful in using the product the first time before they can use it continuously.

Figure 2 - Excerpt from ISO 20282-1, page 5, for designing for usability, mentions that it's important for first-time users of a product to be successful in using the product the first time [29].

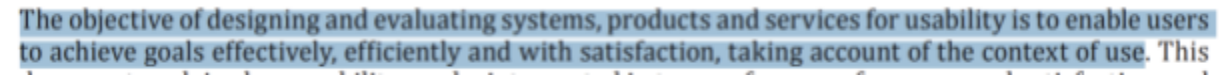


6.3.3 Human effort expended

The human effort used is the mental and physical effort expended to complete specified tasks.

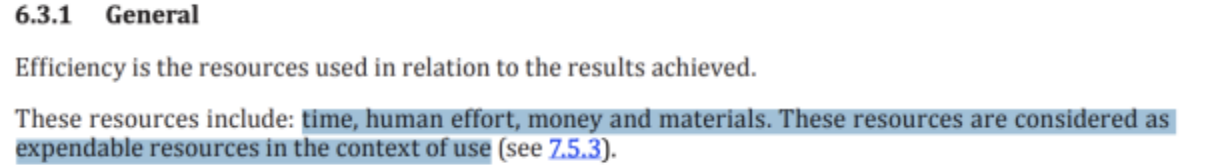
NOTE Human effort deals with the mental and physical impact on the individual user. Expenditure of human effort can involve both excessive demands and underload, either of which can cause negative consequences.

Figure 3 - An excerpt taken from page 11 of [33], discussing how negative consequences can arise from expenditure of human effort.



The objective of designing and evaluating systems, products and services for usability is to enable users to achieve goals effectively, efficiently and with satisfaction, taking account of the context of use. This

Figure 4 - Excerpt taken from page vi (Introduction) of [33], explaining that designing products for usability is done to enable users to achieve their goals with satisfaction.



6.3.1 General

Efficiency is the resources used in relation to the results achieved.

These resources include: time, human effort, money and materials. These resources are considered as expendable resources in the context of use (see 7.5.3).

Figure 5 - Excerpt from [33], page 10, describing that time is an expendable resource in the context of using a product.

liability. Reliability in engineering design may be considered from the points of view of whether a design has inherently obtained certain attributes of functionality, brought about by the properties of the components of the design, or whether the design has been configured at systems level to meet certain operational constraints based on specific design criteria. Designing for reliability includes all aspects of the

Figure 6 - Excerpt from [40], Chapter 3: Reliability and Performance in Engineering Design, page 43, describing what constitutes reliability in engineering design.

nents present at the beginning of the test. A more complete definition of reliability that is somewhat more complex is given in the USA Military Standard (M1L-STD-721B). This definition states: "*Reliability is the probability that an item will perform its intended function for a specified interval under stated conditions*". The definition indicates that reliability may not be quite as simple as previously defined. For example, the reliability of a mechanical component may be subject to added stress from vibrations. Testing for reliability would have to account for this condition as well, otherwise the calculation has no real meaning.

Figure 7 - Screenshot taken from Chapter 3: Reliability and Performance in Engineering Design, page 47 of [40], relaying what reliability is, following USA Military Standard.

In general, the measure of an item's *reliability* is defined as "*the frequency with which failures occur over a specified period of time*". In the past several years, the concept of reliability has become increasingly important, and a primary concern with engineered installations of technically sophisticated equipment. *Systems reli-*

Figure 8 - Screenshot taken from [40], Chapter 3: Reliability and Performance in Engineering Design, page 45, describing how reliability can be defined in engineering design.

troller's job before and after system automation control. Potential safety issues are identified that involve decreased awareness, increased vigilance requirements, and skills degradation. Identification, classification and evaluation of potential hazards

Figure 9 - Screenshot from [40], page 535, depicting how potential safety issues can occur.

of events that could lead from a hazard to an accident or incident. Working through these phases of hazards and safety analysis, and iterating where appropriate, a *safety case* is prepared that relates to the assurance that the system is relatively safe. Haz-

Figure 10 - Screenshot from [40], page 529, depicting that a safety case be available to assure a system is relatively safe.

The safety functions are classified in the following groups (AIChE 1985):

- Safety systems that automatically respond to the initiating event (e.g. automatic shutdown systems).

Figure 11 - Screenshot from [40], page 557, depicting that there should be safety systems that automatically respond to an 'initiating event'.

10.5. Appendix E: Codes and Standards

- *Perspicuity*: Is it easy to get familiar with the product? Is it easy to learn? Is the product easy to understand and clear?

TABLE I

BENCHMARK INTERVALS FOR THE UEQ SCALES

	Att.	**Eff.**	**Per.**	**Dep.**	**Sti.**	**Nov.**
Excellent	≥ 1.75	≥ 1.78	≥ 1.9	≥ 1.65	≥ 1.55	≥ 1.4
Good	≥ 1.52 < 1.75	≥ 1.47 < 1.78	≥ 1.56 < 1.9	≥ 1.48 < 1.65	≥ 1.31 < 1.55	≥ 1.05 < 1.4
Above average	≥ 1.17 < 1.52	≥ 0.98 < 1.47	≥ 1.08 < 1.56	≥ 1.14 < 1.48	≥ 0.99 < 1.31	≥ 0.71 < 1.05
Below average	≥ 0.7 < 1.17	≥ 0.54 < 0.98	≥ 0.64 < 1.08	≥ 0.78 < 1.14	≥ 0.5 < 0.99	≥ 0.3 < 0.71
Bad	< 0.7	< 0.54	< 0.64	< 0.78	<0.5	< 0.3

Figure 1 - Definition of perspicuity, as defined in [30], taken from page 41, and Table 1, taken from page 43, defining what values make a product bad, below average, above average, good, and excellent, for each respective category. “Per.”, in this case, represents perspicuity.

baseline weight or "load constant" (LC) to a recommended weight limit (RWL). A "load constant" (LC) of 23 kg (about 51 lb) was established by NIOSH as a load that, under ideal conditions, is safe for 75% of females and 90% of males.

The recommended weight limit is calculated by using the NIOSH lifting equation.

Figure 2 - Excerpt from the NIOSH main page, describing that a weight limit of around 23kg (or 51lb) is safe for 75% of females and 90% of males [31].

Each of these variables is then assigned a numerical value (multiplier factor) from look-up charts. The NIOSH equation includes six multiplier factors to calculate the recommended weight limit (RWL):

RWL = LC x HM x VM x DM x FM x AM x CM

Horizontal Multiplier (HM): Horizontal distance (H, in cm) from the midpoint between the ankles to the hands while holding the object.

H = Horizontal Distance (cm)	HM Factor
25 or less	1.00
30	0.83
40	0.63
50	0.50
60	0.42

Vertical Multiplier (VM): The vertical distance (V, in cm) of the hands from the ground at the start of the lift.

V = Starting Height (cm)	VM Factor
0	0.78
30	0.87
50	0.93
70	0.99
100	0.93
150	0.78
175	0.70
>175	0.00

Asymmetric Multiplier (AM): The twisting angle (A) of the body while lifting, measured in degrees.

A = Angle (degrees)	AM Factor
90°	0.71
60°	0.81
45°	0.86
30°	0.90
0°	1.00

Distance Multiplier (DM): The vertical distance (D, in cm) that the load travels.

D = Lifting Distance (cm)	DM Factor
25 or less	1.00
40	0.93
55	0.90
100	0.87
145	0.85
175	0.85
>175	0.00

Frequency Multiplier (FM): The frequency (F) of lifts and the duration of lifting (in minutes or seconds) over a workshift.

F = Time Between Lifts	FM Factor			
	Lifting While Standing:		OR Lifting While Stooping:	
	One Hour or Less	Over One Hour	One Hour or Less	Over One Hour
5 min	1.00	0.85	1.00	0.85
1 min	0.94	0.75	0.94	0.75
30 sec	0.91	0.65	0.91	0.65
15 sec	0.84	0.45	0.84	0.45
10 sec	0.75	0.27	0.75	0.27
6 sec	0.45	0.13	0.45	-
5 sec	0.37	-	0.37	-

Coupling Multiplier (CM): The quality of grasp (or coupling, C) classified as good, fair or poor and depends on the body position (either standing or stooping).

C = Grasp	CM Factor:	
	Standing	Stooping
Good (handles)	1.00	1.00
Fair	1.00	0.95
Poor	0.90	0.90

Figure 3 - Excerpts from the NIOSH website, explaining how to calculate the recommended weight limit of a product based on parameters LC, HM, VM, DM, FM, AM, CM, explained in more detail on their website [31].

Most dining tables are made according to standard measurements. The **standard width** is **36-40 inches** while **standard height** is **29-31 inches**.

The length varies depending on how many people the table sits. The seating number varies due to the differences in leg layout of the table and chair sizes.

Seats	Length
4-6	68-72"
6-8	72-80"
8-10	80-92"
10-12	92-110"

Figure 4 - Screenshot taken from World Interior's website, disclosing standard measurement for their tables [32].

MERV	Particle Size Filtered, µm	Types of Particles Filtered	Applications
1-4	<10	Pollen, dust mites	Residential buildings, window air conditioners
5-8	3-10	Mold, spores	Commercial buildings
9-12	1-3	*Legionella*, nebulizer drops	Hospital laboratories
13-16	0.30-1	All bacteria, droplet nuclei, most smoke	Hospital inpatient care, general surgery, smoking lounges

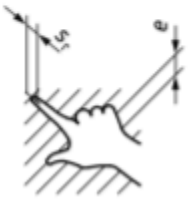
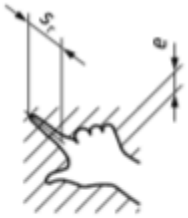
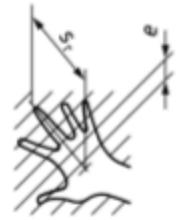
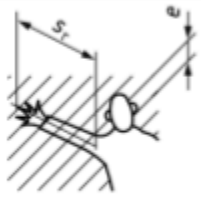
Figure 5 - Excerpt taken from [35], showing a chart of what the associated MERV value is for each type of particle. A MERV value only up until commercial buildings will be applied, considering AFOLs mostly create MOCs from home, and may not require filters that are used in hospital labs and surgical applications.

cycle time
The time, usually expressed in seconds, for a controller to complete one control loop where sensor signals are read into memory, control algorithms are executed, and corresponding control signals are transmitted to actuators that create changes to the process resulting in new sensor signals. [ISADICT]

Figure 6 - A screenshot from page 161 of [39], describing that cycle time is the time for one control loop (for processing one object).

Table 5 — Reaching through regular openings — Persons of 3 years of age and above

Dimensions in millimetres

Part of body	Illustration	Opening	Safety distance to hazard zone, s_r		
			Slot	Square	Round
Fingertip		$e \leq 4$	≥2	≥2	≥2
		$4 < e \leq 6$	≥20	≥10	≥10
Finger up to knuckle joint		$6 < e \leq 8$	≥40	≥30	≥20
		$8 < e \leq 10$	≥80	≥60	≥60
Hand		$10 < e \leq 12$	≥100	≥80	≥80
		$12 < e \leq 20$	≥900[a]	≥120	≥120
Arm up to junction with shoulder		$20 < e \leq 30$	≥900	≥550	≥120
		$30 < e \leq 100$	≥900	≥900	≥900

NOTE The bold line within the table delineates that part of the body restricted by the opening size.

[a] If the length of the slot opening is ≤40 mm, the thumb will act as a stop and the safety distance may be reduced to ≥120 mm.

Figure 7 - Excerpt from [45], page 8, depicting safe sizes of openings on devices.

Lockout is defined in the Canadian standard CSA Z460-20 "Control of Hazardous Energy - Lockout and Other Methods" as the "placement of a lockout device on an energy-isolating device in accordance with an established procedure." A lockout device is "a mechanical means of locking that uses an individually keyed lock to secure an energy-isolating device in a position that prevents energization of a machine, equipment, or a process."

Figure 8 - Screenshot from [47], describing what a lockout is, defined in CSA Z460-20, and why it should be incorporated into devices.

4.1.1 Emergency stop function

4.1.1.1 The purpose of the emergency stop function is to avert actual or impending emergency situations arising from the behaviour of persons or from an unexpected hazardous event.

The emergency stop function is to be initiated by a single human action.

4.1.1.2 The emergency stop function shall be available and operational at all times. It shall override all other functions and operations in all operating modes of the machine without impairing other protective functions (e.g. release of trapped persons, fire suppression).

Figure 9 - the definition of 'emergency stop function' taken from page 3 of [48].