University of Toronto

ESC 101

Wandering Furniture and What to do About It

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Contents

1 Background

The continuous relocation of loose accommodation furniture [1], specifically chairs, presents a large challenge to the smooth running of classes at the University of Toronto. Students entering classrooms may not be guaranteed a seat, and must relocate or retrieve a chair from another location – a time intensive operation, especially in a large room (e.g. MY150). Confirmed through multiple email correspondences and a discussion over the phone with Andy Allen - Manager, Academic Scheduling, ACE (Academic + Campus Events) [2], it was determined that this was a problem in all parts of the campus, especially in OISE (Ontario Institute for Studies in Education) and Bahen (Bahen Centre for Information Technology). The current solution to this problem is a team of paid students (Building Patrol) who are tasked with checking all buildings on campus and relocating chairs to their intended position [2]. Aside from this clear monetary cost, Andy Allen also noted the "unidentifiable cost" in depriving students of easy access to seats. Although loose accommodation furniture includes seating with sleds and glides, this design will specifically exclude those due to their difficulty in relocation[2]. This report explores a proposed solution as well as further steps in the implementation of the solution.

2 Who Cares About Wandering Chairs?

2.1 Students Seated Around Campus

Chairs are used around the university in many different classroom types, ranging from traditional classroom arrangements to mixed media classrooms such as the TEAL rooms [16] in the Myhal Centre. These students include Engineering Science students, which is itself a superset of Engineering Science commuters. Engineering Science students are additionally impacted as they are likely to have classrooms in Bahen where this is a major problem.

2.2 Academic and Campus Events

ACE Manager of Academic Scheduling Andy Allen stated that as the person responsible for all accommodation furniture in classrooms, he has a large personal interest in the design. As alluded to in the introduction, the combination of paid "Building Patrol" positions, as well as the "unidentifiable cost" of students' time, the University has a financial incentive to mitigate this problem. When asked what the university would be willing to spend, he quoted \$50,000 as a "reasonable amount".

[1] Seating with Sled, 4-point or 5-point base, wheels or glides [1].
[2] As explained in 5.1.1, an object which is harder to steal will be less likely to be stolen.

2.3 University of Toronto Facilities and Services Staff

Part of the goal of the Facilities and Services team is to "provide a safe, clean, comfortable, sustainable and attractive environment for the University community" [14]. As such, the caretaking staff are required to clean in and around the chairs and have an interest in the selection.

2.4 Professors and TAs

Professors and TAs who teach in the room have a vested interest in the efficiency of their classes as well as the effective collaboration of their students, which is directly affected by the presence of chairs as well as the utility of the solution.

3 High Level Objective

To encourage organization of chairs in classrooms at the University of Toronto by keeping them in their designated locations for their designated uses.

4 Detailed Objectives

4.1 Organization

1. The solution should prevent removal of a chair from its designated position when it is needed there.

2. Improve collaboration by facilitating free movement of chairs. By allowing a large range of motion, students are able relocate to meet their desired seating arrangement, which is important to effective collaboration [15][18], which would be desired by the students and teaching team alike.

3. However, the removal of a chair to improve collaboration should be followed by the return of the chair to its original position; i.e. the solution should encourage organization by encouraging the users to keep the chairs in their usual positions.

4.2 Physical Limitations

1. Be of reasonable size. If the chairs are made bulky by the addition of the solution, then their functionality will decrease. This may be due to a variety of reasons- the large size may prevent mobility or just the overall convenience of the chair. This sizing must also be in accordance with fire safety codes. This is in the interest of all stakeholders. Additionally, the solution should not be a hindrance to caretaking staff.

2. Be of reasonable weight; the chair should be remain easy to move and use. This is similar to the size objective.

3. The solution should be easy to use; it should not cause undue inconvenience due to its size or placement.

4.3 Cost

1. Reduce cost if possible. Because ACE spends money on rearranging chairs, the goal of any solution should be to cost around as much as the current solution.

5 Metrics, Constraints and Criteria

5.1 Organizational Requirements

1. In order to encourage organized chair placement, there must be an incentive to put it back. By implementing negative consequences, the likelihood of an action from happening again is reduced [33]. Therefore, the system should enable an entity responsible (i.e. ACE or Building Management) to identify users, and therefore consequences to be implemented. It is not a requirement that the design chooses a consequence system, but examples may include a fine, or a suspension from usage of accommodation furniture. A higher rating is given to devices that can more easily identify the user who removes a chair. Rate the system in accordance to the rubric in Table 1. A higher level rating is better as it is desired that users are identifiable.

Level 1	User cannot be identified, or identification is close to impossible.
Level 2	User cannot be identified, but the authorities are alerted.
Level 3	User is automatically identified.

Table 1: Rubric for Consequences

2. As mentioned in the Detailed Objectives, collaboration can be encouraged through allowing free-movement of the chair. Measure the lateral clearance of the chair. Lateral clearance here is defined as the distance that the chair is able to freely move. If the lateral clearance is greater than 10 metres, further measurement is not required. After 10 metres, the communication can no longer be considered in-person [13]. A larger distance is desirable, and should be longer than ECF tethers, which is determined to be inadequate to collaboration in 7.4.

5.1.1 Anti-theft as a Part of Organization

There are many analogues between theft and the high level objective of organization. This is because theft is defined as “to deprive, temporarily or absolutely, the owner of it, or a person who has a special property or interest in it, of the thing or of his property or interest in it” [17]. Hence, we can define our organization goal as theft, since a relocation of a chair is a temporary deprivation of the chair. The following additional requirements will be used to rate the system for organization:

1. Conspicuousness is a good measurement of the likelihood of theft [4]. The basis for this is the idea that theft is a crime and therefore not desirable in the general population. Thus people committing theft would be less likely to commit the crime if people are likely to notice while the larceny is in-progress. The system is to be rated with the rubric in Table 2.

Unacceptable	Theft is completely concealable / it is near impossible for the theft to be noticed.
Satisfactory	The theft is noticeable to the keen observer.
Good	A large portion of observers are able to notice the theft.
Excellent	All observers are able to notice theft; Authorities can be alerted.

Table 2: Rubric for Conspicuousness

2. A high complexity anti-theft system will deter larceny from occurring [6]. The complexity of the system will be measured indirectly through the number of operations required to disable the anti-theft system. Although this measurement does not account for some operations being more difficult than others (i.e. blow-torching being more difficult than cutting a tether), a metric must be measurable. For example, a metric ”time taken to disable anti-theft system” would be impossible to measure without user-testing, which means that an anti-theft system must be set up, as well as a large sample of thieves must be acquired to rate the system. Hence, measuring the number of unique operations required to disable the anti-theft system is an acceptable metric. A larger number of operations is advantageous (complexity is increased).

3. Developed from ISO 22448:2010 on Anti-theft systems for Earth-moving machinery [10], we define the system levels in Table 3 to classify theft protection systems. Although the standard is describing systems for protecting anti-theft machines, the system levels have been shown by the document to be an effective way to classify anti-theft systems. In order to make it relevant to furniture, the system levels have been adapted. A higher system level is better, and the minimum system level is 2 (this design is a system).

Level 1	No System.
Level 2	Requires a system for use.
Level 3	User must be authenticated for use.
Level 4	All the properties of 3 in addition to an immobilizer system.

Table 3: System Levels for Anti-Theft System Classification

5.2 Physical Requirements

1. In accordance with the organization objectives, the added mechanism must not inhibit movement or provide an obstacle in the usage/convenience of the chairs. Each device is

to be examined to test whether it maintains the functionality of the chair; the result will be a "Yes/No" rating, with "Yes" if the functionality of the chair were not affected, and "No" if the functionality were affected in any way. "Yes" is preferred.

2. In addition to being a reasonable size, in order to not be a hindrance to care-taking staff, the chairs must be able to be removed temporarily by authorized individuals. Without removal of chairs, janitorial staff must clean in and around the furniture, which requires more time and effort from staff. If chairs are able to be removed by the staff, the chairs can be removed as an obstacle to cleaning. As a "Yes/No" rating, "Yes" is desirable, but not required.

3. Weight is an essential metric in ensuring that the modified chair is easy to move and use, as per the Physical Requirement Detailed Objective. The total weight of the chair and the added mechanism should not exceed the average weight of an office chair[19]. This is a flexible constraint because there are numerous different types of free-moving chairs, and with chairs which already exceed this average value this requirement should be considered, but not required. The rating will be a "Yes/No", with "Yes" being preferred.

4. The solution is also required to be easy to use and not cause inconvenience to students. This can be measured indirectly by measuring the number of unique operations required to utilize the chair. Again, this is problematic since it does not account for different unique operations being different in difficulty, the lack of user-testing makes it difficult to rate more accurately. In any proposed solution, further verification and validation of this metric must be completed. A lower number of operations is ideal.

5.3 Cost Requirements

In the previously mentioned advisement with Andy Allen, he stated that a reasonable amount the University would be willing to spend would be about $50 000. Additionally, we were given that the number of loose chairs (as defined by ACE) was 10 293. This figure includes sleds and glides (which we are not including), which means that the cost per chair should be at least <$5 (rounded up from $4.86), although this is not a hard limit due to the approximate figures given by Andy Allen. Lower costs are favourable.

6 Engineering Process

6.1 Divergence Part 1: Wishing

In the first divergence process, Wishing was chosen as the primary tool for brainstorming different candidates that could be considered in the design. The divergence method's expansive and creative nature was adequate for this procedure since the purpose of this divergence was to create as many alternatives as possible. The SCAMPER tool was also introduced to assist in further divergence. The result was nearly twenty unique candidates which ranged from AI surveillance to biodegradable, one-use chairs. Some constraints originating from our objectives allowed for the reduction of this list to a more compact and realistic set of alternatives, which were then put through the following convergence process.

6.2 Convergence Part 1: Pairwise

Ten candidates from the Wishing divergence were evaluated through an MCDM Pairwise matrix. Since the goal of this convergence process was to narrow the candidates down to three, holistic comparison was deemed sufficient. After a series of evaluations based on our objectives and metrics, three candidates were selected for their outstanding performance—wheel-lock, anti-theft tag and docking station.

6.3 Divergence Part 2: SCAMPER

Reframing and rescoping produced modified objectives and metrics, which called for an additional round of divergence. However, considering that the existing alternatives were still suitable for the modified objectives and metrics, it was decided that SCAMPER is the most reasonable tool for this purpose. Each of the three alternatives led to the creation of two or three additional alternatives, increasing the number from three to ten potential candidates.

6.4 Convergence Part 2: Pugh

For the final convergence process, the ten candidates created in the SCAMPER process were rated and put into a Pugh Chart. Pugh was beneficial because it provided another mechanism through which the candidates were ranked, and gave a more analytic breakdown of each alternative with respect to the specific metrics. The outcome was surprisingly very similar to the first round of convergence, with the slight exception being the shopping cart wheel-lock alternative being eliminated due to the emergence of a higher-ranked wheel-lock with alarm.

7 Potential Solutions

7.1 Shopping Cart Wheel Lock

This solution would implement an idea similar to shopping cart locks used in large supermarkets. It would replace one of the casters on rolling chairs with a specialized caster with brakes and a sensing chip. When the chip detects that it has left the premises by detecting a RF enabled strip at the door, it activates the brakes and locks the chair, making it much more inconvenient for the person removing the chair to proceed. It would add to conspicuousness because the person removing the chair would be required to either carry the chair or drag it. An alarm could be implemented as well to increase the conspicuousness further. Because the caster needed to make this a viable solution does not exist, it would have to be design from scratch using the existing shopping cart wheel lock as reference.

7.2 Anti-Theft Tags

Anti-Theft Tags are widely used in retail to prevent removal of valuable merchandise from the premises. They do so by attaching an RFID tag to the merchandise which is detected by two bars at the doors which activate an alarm when they sense such a tag. This anti-theft design makes use of conspicuousness as its main mode of deterrence, alerting the appropriate authorities when necessary. For use in our chairs, the cost for an individual chair would be quite cheap, as it would only involve attaching such a tag to the underside of the chair. A small enclosure could be added to prevent its removal.

7.3 Docking Station

The docking station is a unique idea which combines the positive aspects of authentication while encouraging organization in the room. Beside each chair, a small enclosure is placed which accepts a caster inside. When the caster is inside, it is locked in place, which prevents the removal of the chair. When the docking station receives an authentication signal, it registers the name of the person who unlocked it and allows the chair to roll freely. Unless the chair is replaced, the system knows who has used the chairs and can provide that information to the proper authorities. The docking station encourages organization because it imparts a sense of responsibility and accountability to the user which increases the chances that the user will return the chair [32]. Several refinements to the initial design could be made where the chairs themselves are registered to users which would allow for any chair to be returned to any docking station, as long as the order of the chairs themselves does not matter, as long as there are chairs in the appropriate places.

7.4 Tethers (Reference Design)

The tethers are the current implementation of organizational solutions in the ECF labs [9]. They prevent removal from the premises of the chairs, and also keep the chairs organized by never allowing them to leave their designated place. However, the physical nature of the tethers makes them inconvenient, as their one benefit of organization detracts from their collaborative nature. They prevent users of the labs from interacting with one another. In addition, the tethers themselves are annoying, preventing easy movement of the chair.

7.5 Combinations

Although each solution addresses the problem to some degree, combining them is useful to examine what exactly makes them good solutions. The combination examined here is the anti-theft tag plus shopping cart wheel lock plus docking station solution. It combines the positive aspect of the shopping cart wheel lock in increasing the inconvenience of taking the chair as well as the conspicuousness of the anti-theft tag alarm system. It also includes the authentication system of the docking station. The main downside of the combination is the increased cost.

8 Picking a Solution

This section will proceed by outlining the reason each alternative received its rating. The ratings are tabulated below, and a Pugh Chart comparing the ratings follows.

8.1 Organization

8.1.1 Tether

The tether rates 1 in organization. Upon theft or removal of the chair from it's designated space, authorities are not alerted nor able to identify the person responsible for the action.

8.1.2 Docking Station

The Docking Station rates 3 in organization. Because it requires authentication, it automatically records who is using the chairs. Therefore, when a chair goes missing, it is registered to the user which causes instant identification.

8.1.3 Wheel Lock

The wheel lock rates 1 in organization. Because it does not include any active method of identification, whether the user can be identified relies on other systems such as security cameras and present observers. If the user successfully dodges these auxiliary systems, it will not be possible to identify or alert authorities of who the user was.

8.1.4 Anti-Theft Tag

The anti-theft tag rates 2 in organization. It does not include a mode of identification, so there is no incentive for the user to return the chair to its designated position. However, it is able to trigger an alarming system which alerts authorities and increases the likelihood of identifying the user.

8.1.5 Combination

The combination inherits the 3 rating from the docking station. The authentication system provides an incentive for the user to return the chair to its original position.

8.2 Simplicity

8.2.1 Tether

The tether rates 0 in simplicity. There are no supplementary steps in being able to use the chair.

8.2.2 Docking Station

The docking station rates 3 in simplicity. This is due to the following 3 required steps involved before being able to use the chair:

- Swiping the student T card
- Choosing the chair in the room to be accessed
- Removing the chair from the docking station

8.2.3 Wheel Lock

The wheel lock rates 0 in simplicity. The locking of the wheels will be automated when the chair reaches a certain point away from the room, and does not add any supplementary steps when accessing the chair.

8.2.4 Anti-Theft Tag

The anti-theft tag rates 0 in simplicity. Similar to the wheel lock, the anti theft system will be automated and does not add any supplementary steps when accessing the chair.

8.2.5 Combination

The combination of the wheel lock and the anti-theft tag rates 3 in simplicity as it is the sum of all operations required in using the chair between the docking station, wheel lock, and anti-theft tag.

8.3 Conspicuousness

8.3.1 Tether

The tether rates "Good" in conspicuousness. Although there is no method of alerting the authorities, the tether connecting the chair to the desk must be cut or removed from its place, which is notifiable.

8.3.2 Docking Station

The docking station rates ”Excellent” in conspicuousness. Upon theft or misplacement of the chair, the chair is both notifiable of its absence from the docking station. The authorities shall be alerted and able to identify the student that is responsible for the action.

8.3.3 Wheel Lock

The wheel lock rates ”Good” in conspicuousness. Although the wheels lock when the chair is not at its designated area, authorities are not alerted.

8.3.4 Anti-Theft Tag

The anti-theft tag rates ”Excellent” in conspicuousness. An alarm will go off when the chair leaves its designated area, and it will be obvious to observers that the chair has been misplaced.

8.3.5 Combination

The combination shares all aspects of conspicuousness for each alternative, so it is rated ”Excellent”.

8.4 Complexity

8.4.1 Tether

The tether rates 1 in complexity. At minimum, the tether must be cut or detached from the table in order to be removed from its designated space.

8.4.2 Docking Station

The docking station rates 3 in complexity. In order for the chair to be stolen, the user must (at minimum):

- Swipe the student T card
- Choose the chair in the room to be removed
- Remove the chair from the docking station

8.4.3 Wheel Lock

The wheel lock rates 1 in complexity. At minimum, the chair must be lifted over the area that activates the wheel locking mechanism.

8.4.4 Anti-Theft Tag

The anti-theft tag rates 0 in complexity. There are no supplementary actions required to displace the chair from its designated area.

8.4.5 Combination

The combination rates 4 in complexity. It requires all the operations for each alternative, which sums to 4 operations.

8.5 Systems

8.5.1 Tether

The tether rates 0 in systems. There is no system for its use.

8.5.2 Docking Station

The docking station rates 4 in systems. The user is authenticated before use of the chair and the docking station acts as an immobilizer system.

8.5.3 Wheel Lock

The wheel lock rates 1 in systems. There is no system for its use.

8.5.4 Anti-Theft Tag

The anti-theft tag rates 1 in systems. There is no system for its use.

8.5.5 Combination

The combination rates 4 in systems, since it includes all features of the 3 alternatives (docking station rates 4 in systems).

8.6 Cleaning

8.6.1 Tether

The tether receives a "No" for this metric because the chairs cannot be temporarily removed.

8.6.2 Docking Station

The docking station receives a "Yes" for this metric because the chairs can be temporarily removed when needed.

8.6.3 Wheel-Lock

The wheel-lock receives a "Yes" for this metric because the chairs can be temporarily removed when needed.

8.6.4 Anti-Theft Tag

The anti-theft tag receives a "Yes" for this metric because the chairs can be temporarily removed when needed.

8.6.5 Combination

The combination receives a "Yes" for this metric because the chairs can be temporarily removed when needed.

8.7 Cost

8.7.1 Tether

The cost was determined by shopping online for the cheapest bicycle lock with physical resemblance to the tethers used in the ECF labs. That cost was determined to be $1.52.

8.7.2 Docking Station

The cost is discussed in the prototyping section below. The cost of the docking station was determined to be $8.17. A note to the reader— this is an example of going back and idealizing the real process. However, because of this inconsistency it would not be fair for the our defining metric to be cost; because it is logically inconsistent for it to have been. As a side note, for the injection molding cost estimate, a material with the same price as PVC was selected to get an accurate measure of how much it would cost to injection mold the parts.

8.7.3 Wheel Lock

The cost was determined by obtaining a quote from a shopping cart wheel lock manufacturer for a similar amount of shopping carts as there are free-moving chairs on campus. This came out to $11.22 per chair.

8.7.4 Anti-Theft Tag

Anti-Theft tag costs were estimated by searching for an anti theft system online. One was found on AliExpress, and if it was installed in the biggest ECF lab the cost would be $1.67 per chair.

8.7.5 Combination

The cost of the combination was found by adding up the costs of the other three. This is a reasonable assumption because they do not share any components that could be reused for multiple systems; as such the component costs form non intersecting sets.

8.8 Collaboration

8.8.1 Tether

The tether rates 1.52 in collaboration as this is the length of the tether that provides free movement of the chair [3].

8.8.2 Docking Station

The docking station allows for free movement so it is rated "greater than 10" for collaboration.

8.8.3 Wheel Lock

The wheel lock allows for free movement so it is rated "greater than 10" for collaboration.

8.8.4 Anti-Theft Tag

The anti-theft tag allows for free movement so it is rated "greater than 10" for collaboration.

8.8.5 Combination

The combination of alternatives allows for free movement so it is rated "greater than 10" for collaboration.

8.9 Tabulation

8.9.1 Ratings Matrix

The ratings matrix (Fig 1) is the culmination of all the above subsections, combining all the ratings into a cohesive table. It is converted to a Pugh Chart below (Fig 2).

8.9.2 Pugh Chart

In this Pugh chart, the number of pros and the number of cons are recorded in the bottom row. Note that they are not sums of the whole column, but rather tallies of the number of benefits and number of detriments of each alternative against the reference design.

In this Pugh Chart, the combination alternative has the most pros. Coming in second is the docking station, which has five pros. However, the alternative we picked to develop was the docking station. Because the combination costs so much and only improves the complexity of the solution, we viewed it as a marginal increase for a large increase in cost and labor.

Metric	Tether	Docking Station	Wheel Lock	Anti-Theft Tag	Combination
Organization	1	3	1	2	3
Simplicity	0	3	0	0	3
Conspicuousness	G	E	G	E	E
Complexity	1	3	1	0	4
Systems	1	4	1	1	4
Cleaning	N	Y	Y	Y	Y
Cost	5	9.01	11.22	1.67	21.06
Collaboration	1.52	>10	>10	>10	>10

Figure 1: This is a ratings matrix which compiles all above ratings sections.

Metric	Tether	Docking Station	Wheel Lock	Anti-Theft Tag	Combination
Organization	0	+	0	+	+
Simplicity	0	-	0	0	-
Conspicuousness	0	+	0	+	+
Complexity	0	+	0	-	+
Systems	0	+	0	0	+
Cleaning	0	+	+	+	+
Cost	0	-	-	+	-
Collaboration	0	+	+	+	+
Totals	0/0	+6/-2	+2/-1	+5/-1	+6/-2

Figure 2: This is a pugh chart which is derived from 1

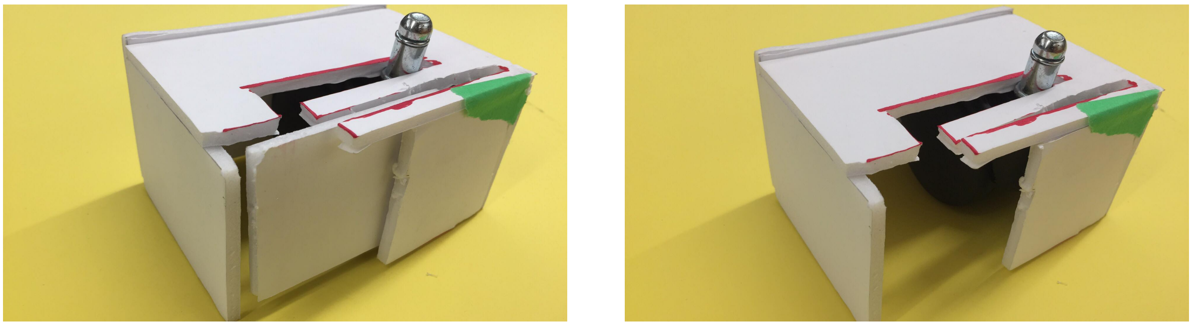
The projected cost of the docking station was $8.17 CAD, with ways to decrease the cost. Because the combination was three times more expensive, and at minimum three times as hard to implement, it was not the alternative we picked.

9 Docking Station Prototyping

We proto-typed the Docking Station in two ways: through physical foam-core prototyping and through a cost analysis of the required components.

9.1 Physical Prototypes

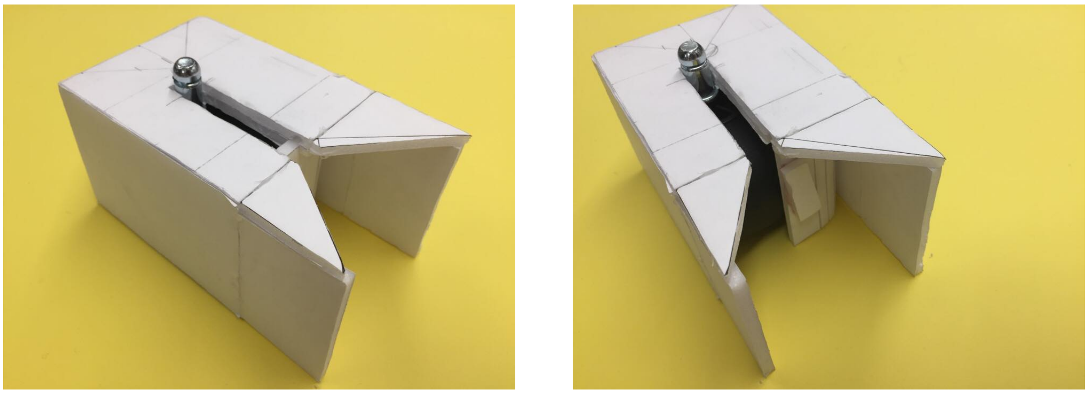
Pictures of the physical prototypes are recorded in Figures 3 and 4.



(a) Closed (b) Open

Figure 3: The first foam-core prototype. Note that the in (a) the door is closed, preventing a caster from exiting.

In the first prototype, we realized it was difficult to direct the caster into the docking station. To ameliorate that inconvenience, we designed a second foam-core prototype with a two slanted plates extended out in front of the station, directing the metal part of the caster into the station. To decrease the profile of the docking station, the door type was changed into one that bent and folded into the side of the docking station, much like the mechanism on a garage door. This is shown in Figure 4.



(a) Closed (b) Open

Figure 4: The second foam-core prototype. The funnel makes it much easier to direct the caster into the docking station.

9.2 Cost Prototyping

The second method of prototyping included picking out the parts needed to implement the docking station. This prototyping method is described in the following parts lists, with explanatory paragraphs to accompany them.

The physical docking station could be built from the materials in Figure 5.

Component	Cost	Source:
Motor	$0.12	AliExpress [41]
Plastic Housing	$2.89	Custompartnet [42]
Gearing	$1.64 + $2.94	McMaster-Carr [43]
Radio Transceiver	$0.24	LCSC [39]
Attiny24A-SSU	$0.83	LCSC [44]
Total	$8.66	

Figure 5: The cost of the major components for an implementation of the second foam-core prototype.

The electric motor would be needed to actuate the door mechanism on the docking station. Such motors are easily acquired for very cheap through websites such as AliExpress. The gearing was sourced through McMaster-Carr, an industrial supply company. For our foam-core prototypes, gears would be needed to convert the rotary motion of the motor into the linear motion of the door mechanism. Further prototypes could remove the need for gearing, further reducing cost. For example, a circular door could be used, which would be attached through direct-drive to the motor, eliminating the need for any gearing. A radio transceiver would allow the docking station to communicate with the control panel, or whatever system controls the motion of the docking station. One implementation for the ECF labs is described below. The radio transceiver would communicate with an ATMega48PA-AU, which is a micro-controller. It would take in the radio signal from the transceiver and actuate the motor.

Component	Cost	Source:
3.5" Touch Screen	$14.52	Zapals [36]
5V AC-DC Converter	$0.89	AliExpress [37]
Raspberry Pi Zero	$11.87	AliExpress [38]
Radio Transceiver	$0.24	LCSC [39]
Magnetic Card Reader	$13.20	AliExpress [40]
Total	$40.72	

Figure 6: The cost of the major components for a wall mounted control panel.

The usage of this wall mount panel is as follows. First, the user will swipe their T-card in the Magnetic Card Reader. The Raspberry Pi Zero will bring up an interactive picture of the classroom, displaying all available chairs. The user selects one on the touch screen, and that docking station will be unlocked through communication by the radio transceiver. These components are the cheapest of their kind that we could find; however the costs might be reduced in a real implementation because of bulk ordering and better sourcing of components. The 5V AC to DC converter powers the wall mounted mechanism.

This method of tallying component costs both serves as a method of prototyping and a method of verifying whether our designs meet our cost objectives. The two component tallies above are for implementation in the ECF labs. In the biggest ECF lab, the cost of one wall mount panel and 117 docking stations split among each workstation yields a total cost of 9.01 per chair. Verifying this against our cost objective reveals that we are over the five dollar limit per chair. Thus we look back at the costs and see what materials are not necessary. When we remove the gears as described in the above paragraph, we can cut our cost per chair down to $4.42 per chair— quite cheap.

10 Detailed Design Decision - Material Selection

10.1 Purpose

In order to rate our proposed solution for cost, a material must be selected.

10.2 Objectives

10.2.1 Be Aesthetically Pleasing

As a reference to the primary stakeholder, the students, the material choice must be able to be made to be aesthetically pleasing. A study by the University of Salford concluded that aesthetics of a classroom was important to learning [18].

10.2.2 Be Low-Cost

In relation to the original cost objective (described in 4.3), the material must be cheap to manufacture.

10.2.3 Be Waterproof and Dust Resistant

The docking station would be implemented on the floor, and as such is subject to water carried in through footwear (i.e. snowing or raining outside). Additionally, students may spill water and other fluids onto the docking station. Therefore, the material must be impermeable to water. Dust also collects on the floor, so dust should not impede the performance of the solution.

10.2.4 Be Resilient

As suggested above, due to the implementation on a floor, the docking station should be able to resist intentional and unintentional damage, which may be caused by users, as well as general wear and tear due to the environment.

10.2.5 Be Manufacture-able

As there are about 10,293 loose chairs at the University of Toronto alone[2], each requiring a docking station, injection moulding is the ideal manufacturing technique [12]. Since this solution is generalized, this product may also be used at other institutions or businesses, which makes mass-manufacturing even more important. Therefore, the material must be injection mould-able.

10.3 Requirements

10.3.1 Aesthetics

The material inherently should not inhibit the appearance of the docking station, since different applications of the docking stations may want to customize the appearance in different ways (i.e. match colour scheme of the room/building). Thus, the aesthetics shall be rated with regards to the rubric described in Table 4. Since it was determined by Barett *et. al.* [18] that aesthetics are important to learning, the minimum shall be Satisfactory. The table is ordered in such a way that the ratings going down the table are in order of increasing preference.

Unsatisfactory	Appearance of material cannot be changed from its raw appearance.
Satisfactory	Colour of the material can be changed.
Good	Colour and complex patterns can be made.
Excellent	Etchings can be made; Arbitrary designs can be made on the material.

Table 4: Rubric for Aesthetics

10.3.2 Low-Cost

It is obvious that different materials have different costs, and that the quantity of a material used will affect the overall cost. The price of a material (units of price/mass) and the density of that material (units of mass/volume) can be multiplicatively combined to create a rating in units of ($/kg). These measurements will be taken from *Materials and Design - The Art and Science of Material Selection in Product Design (2nd Edition)* [29]. A lower cost is preferred.

10.3.3 Water and Dust

Rate the product in accordance to CSA C22.2 No. 60529:16 (or IEC 60529:1989 if Canadian standards are not available) [3]. Should be at least IP54 resistant (5 = Dust-protected, 4 = Splashing splashing). These values were chosen as a result of typical usage as described in 10.2.3. There is no hard constraint since there is a cost-protection trade-off, as an increase in material and design cost can increase the protection rating. However, as described in 5.1.1, any hindrance to a potential theft/removal decreases the potential of it occurring. Additionally, this rating would require extensive testing of the complete product (i.e. evaluate the material and design holistically). In order to remove this requirement so that a material selection can be done at this preliminary stage, we will only be considering whether the material is impermeable to liquid water or not. "Yes" is required.

10.3.4 Resiliency

1. In order to remain resilient through general wear and tear, the material must not be easily corroded, since corrosion can severely degrade the material and lead to mechanical failure, which is undesirable in a product that is expected to last such as this solution (due to low-cost objective – replacement is undesirable) [23]. Therefore the material should not be easily corroded. The rating will be given by considering if the material is easily corroded. "No" is preferred.

2. Through everyday wear and tear, it is expected that the material is able to resist impacts from various sources. Since it is placed on the ground, sources of such impacts may include being stepped on as well as objects colliding with it after experiencing acceleration largely comprised of the gravitational force. Due to the objective of being manufacture-able, as described in 10.2.5, the material selection has been limited to thermoset plastics [20]. A good indicator of plastic strength is the Notched Izod Impact Test, as described by ISO 180:2000[11]. The rating will be taken from the *Complete Part Design Handbook - For Injection Moulding of Thermoplastics* [5], which gives a rating for the Notched Izod Impact Test @ 73°F in (ft-lb/in). Just as in 10.3.3, there is a cost-resiliency trade-off. Thus, there is no constraint for this metric, but a higher number (meaning more energy can be absorbed) is better.

10.3.5 Manufacturability

In order to be manufacture-able, the material must be injection mould-able (reasoning described in 10.2.5). Whether or not it is injection mould-able must be "Yes", which is better than "No".

10.4 Determining Feasible Alternatives

In order to fit the injection mould-able constraint, the acceptable materials must be limited to thermoplastics, for which a list can be found in *Complete Part Design Handbook - For Injection Moulding of Thermoplastics* [20]. From this the following materials were chosen due to be considered as they were some of the most commonly used plastics [24]. Note that the alternatives chosen are still quite general, since almost all these polymers can be changed to have different features [7], so we will only look at these polymers with typical attributes from typical applications.

1. **Polyethylene**: Polyethylene is the most commonly used plastic in the world. It is commonly used to make plastic bags, shampoo bottles, children's toys, and bullet-proof vests [21].

2. **Polyvinyl Chloride**: PVC is also widely used, although not in as direct contact as Polyethylene. It is commonly used in scaffolding billboards, fresh and waste water pipes, window frames, and interior design articles [22].

3. **Acrylonitrile Butadiene Styrene**: As all the other plastics in this list, ABS is also widely used, and competes with Polypropylene and some grades of PVC, being less stiff. In previous years, ABS was largely used as a prototyping material since it can be easily manufactured [24], but can now be used to replace even metal parts [25].

4. **Polycarbonate**: Polycarbonate is a transparent plastic with very high impact resistance, making it popular for use in automotive light reflectors, flashlight lenses, and heat resistant helmets [26].

5. **Nylon**: Nylon is a polymer that is known as "an engineering thermoplastic", due to its toughness and rigidity, should made it suitable for mechanical bearings. It's performance sometimes surpassed those of metal [27].

10.5 Rating Alternatives

10.5.1 Aesthetics

1. **Polyethylene**: Polyethylene accepts a wide range of colours and transparencies, can be textured, but cannot be easily printed on (no arbitrary designs) [28]. Therefore, Polyethylene rates Satisfactory in terms of aesthetics.

2. **Polyvinyl Chloride**: PVC can be customized in many ways, including colour and texture (can be made to resemble leather even). It's tough nature makes it etch-able [29]. PVC is hence Excellent in aesthetics.

3. **Acrylonitrile Butadiene Styrene**: ABS takes colour well, and is tough, making it etch-able [30]. ABS also rates Exellent in aesthetics.

4. **Polycarbonate**: Polycarbonate readily takes colour, but cannot be easily printed on (no complex patterns) [31]. Polycarbonate rates Satisfactory in aesthetics.

5. **Nylon**: Nylon can be made to accept print and colour, but its fibrous nature makes it difficult to make etchings [32]. Therefore Nylon rates Good in aesthetics.

10.5.2 Low-Cost

1. **Polyethylene**: Taking a price of \$4.00/kg and a density of 1.4 Mg/m^3 [28] gives a cost of \$5600/m^3.

2. **Polyvinyl Chloride**: Taking a price of \$1.20/kg and a density of 1.58 Mg/m^3 [29] gives a cost of \$1896/m^3.

3. **Acrylonitrile Butadiene Styrene**: Taking a price of \$2.80/kg and a density of 1.21 Mg/m^3 [30] gives a cost of \$3388/m^3.

4. **Polycarbonate**: Taking a price of \$4.30/kg and a density of 1.21 Mg/m^3 [31] gives a cost of \$5203/m^3.

5. **Nylon**: Taking a price of \$11.50/kg and a density of 1.42 Mg/m^3 [32] gives a cost of \$16330/m^3.

10.5.3 Water and Dust

For the plastics discussed, permeability to liquid water is basically negligible [34] [35]. Therefore, all alternatives rate "Yes" to this.

10.5.4 Corrosion

1. **Polyethylene**: Polyethylene is inert, and is extremely resistant to most water-based solutions [28]. Polyehtylene rates a "No" for corrosion.

2. **Polyvinyl Chloride**: Polyvinyl Chloride has excellent resistance to acids, bases and atmospheric gases [29]. Polyvinyl Chloride rates a "No" for corrosion.

3. **Acrylonitrile Butadiene Styrene**: ABS can be made to be very chemically resistant, with additives such as UV stabilizers [30]. ABS rates a "No" for corrosion.

4. **Polycarbonate**: Just as with all the previous mentioned polymers, Polycarbonate behaves similarly in that everyday materials will not corrode the material [31]. Polycarbonate rates a "No" for corrosion.

5. **Nylon**: Nylons have poor resistance to strong acids and oxidizing agents [32]. Nylon rates a "Yes" for corrosion.

10.5.5 Impact Strength

All the following Notched Izod Impact Test results are from *Complete Part Design Handbook - For Injection Molding of Thermoplastics* [5], which performs the test @ 73°F, and gives results in (ft-lb/in).

1. **Polyethylene**: 9.5

2. **Polyvinyl Chloride**: 20.0

3. **Acrylonitrile Butadiene Styrene**: 12.0

4. **Polycarbonate**: 3.0

5. **Nylon**: 2.50

10.5.6 Manufacturable

All five alternatives rate a "Yes", due to the requirement of the materials being a thermoplastic. Further discussion of selected alternatives are present in 10.4.

10.6 Tabulation

10.6.1 Ratings Matrix

In the following ratings matrix (Table 5), the ratings to the metrics explained above will be enumerated. The alternative and metric numbering are in order that they are listed in 10.4 and 10.3 respectively. "Unsatisfactory", "Satisfactory", "Good", and "Excellent" ratings have been shortened to "U", "S", "G", and "E", respectively. Similarly, "Yes" and "No" have been shortened to "Y" and "N".

	M1	**M2**	**M3**	**M4**	**M5**	**M6**
A1: Polyethylene	S	5600	Y	N	9.5	Yes
A2: PVC	E	1896	Y	N	20.0	Yes
A3: ABS	E	3388	Y	N	12.0	Yes
A4: Polycarbonate	S	5203	Y	N	3.0	Yes
A5: Nylon	G	16330	Y	Y	2.50	Yes

Table 5: Ratings matrix of materials

10.6.2 Pairwise Comparison Chart

Due to the requirement that the material be integrated into the entire product design, it makes sense that the material choice be evaluated holistically in relation to the product. The chart is found in Table 6.

	A1	A2	A3	A4	A5
A1	0	+	+	-	-
A2	-	0	-	-	-
A3	-	+	0	-	+
A4	+	+	+	0	-
A5	+	+	-	+	0

Table 6: Pairwise comparison chart of materials

Hence PVC (A2) will be the selected material. It is a very cheap, yet resilient material, which can be customized in many ways. Its properties allow it to be mass manufactured.

11 Next Steps

In order to bring this idea to production and implementation, several aspects of this design review must be extended and elaborated on. To begin, the physical prototypes could be improved in their general design, as discussed above. The door mechanisms do not need to be very complicated, and the device could be set up so that force applied to the door would be transferred to the enclosure and not the motor. This would eliminate the potential damage to the motor from attempts to force the chair out of its enclosure. However, this would make the plastic casing more complex, which would increase its cost to injection mold. In large scale production, > 10000 units, these increases in cost would be marginal [42]. Such a design would need to be modeled in CAD and then sent to a production facility to be manufactured.

The authentication systems could also be improved. In the example implementations, one fairly simple method would be to release the chair when the ECF computer is unlocked. Although the user having to stand up while typing up is a minor inconvenience, it is better than having to go to another part of the room to unlock the chair.

Different room types also must be considered. Because the ECF labs do not function on tight time schedules with limited and rigid time for lecture, a wall mounted monitor would suffice. However, for a classroom where every student comes in at the same time—i.e. high rates of student influx all at once, the monitor would slow down the start of class and inconvenience the users of the classroom. A more efficient and universal system may be necessary for these rooms.

The technical aspects of the prototypes that were glossed over in the cost prototyping section must be elaborated on and created. For the docking station, the ATMega must be loaded with an appropriate program which can read in the radio transceiver signal. This would be written in C, and the appropriate datasheets for the components would need to be referenced when writing that program. For the wall mounted panel, the program could be written in Python for ease of development. Similarly the radio transceiver would have to be interfaced with Raspberry Pi Zero, or any even cheaper microprocessor with the necessary capabilities— the ability to drive the display and the interface with the USB mag-stripe reader and the transceiver. For both of these, a dedicated PCB would be made with all the components on a single board.

Several use cases would have to be considered when programming the docking station and the main controller. When staff want to clean the room, they could swipe their cards and have all the docking stations automatically unlock, allowing them to easily move the chairs to vacuum and mop the floors. Another use case would be if someone wanted to use the entire room for an event— they would not want the guests who might not even have TCards to have to authenticate themselves to use the chairs. Cards with the proper authority could be allowed special access privileges, or the system could provide the option of giving those special access privileges only at a certain time, perhaps in relation to a departmental or events schedule.

Similarly, the appropriate consequences for violation of the chair replacement rules would have to be decided on by administration, presumably those at Academic + Campus Events. Potential consequences could be fines, restriction from the facilities in which the incidents occurred, or other suitable punishments.

The easiest and most pressing validation step is to run this design past the person who corroborated the entire design review, Andy Allen. If he believes that the review is worth pursuing, then this would be a major validation of the solution.

12 Changes from the Design Brief

This design review has evolved significantly from the original design brief. The brief focused mainly on designing an entirely new chair, which would aim to increase collaboration while preventing the chairs from being stolen. After completing the design brief, we decided to re-scope our high level objective to focus on theft since there were not many ways of measuring collaboration aside from the proximity of the chairs. Another contribution to the re-scope was that after using the wishing method of diverging and system 1 converging, we noticed that most of our alternatives were related to theft. However, after the alpha release, we realized that there was not sufficient grounding as we did not have a credible source for justifying that theft was an issue in the first place. In this design review, the high level objective now focuses on the problem of wandering furniture, which is inherited from the idea of the chairs being stolen. The grounding for this design review has improved significantly due to the evidence gathered from Andy Allen. As such, the subject of collaboration has been moved to the detailed objective section. In addition, the scope of this design review has changed from the chairs in the MCEIE to all free moving chairs on campus.

The objectives now include cost as a more major and concrete factor, mentioning actual dollar values. Organization is a new objective that was not in the brief— we now want to keep the chairs organized within the classroom, not just prevent them from leaving the space. The metrics have also undergone significant revision— all metrics for ergonomic considerations have been removed, as we are no longer considering the design of an entire chair, but rather a solution for an added mechanism. The organizational requirements are now a large part of the metrics section. Weight and size metrics were kept in lieu of the desire to keep our add-on solutions as convenient as possible.

Further changes were added because the current document is a design review and not a design brief; as such it includes the solutions we came up with, the engineering process, prototyping, a material decision section, and a next steps section.

In light of the extensive changes, the appendix has been updated in support of all new assertions.

Source Extracts

[1] "Design Criteria For Classrooms", *Academic + Campus Events*. https://ace.utoronto.ca/standard/standards_ut/Design%20Criteria%20for%20Classrooms%202012_07_09.pdf.

SEATING	Loose	Sled, 4-point or 5-point base, wheels or glides Upholstered or non-upholstered
	Fixed	Theatre floor mount, on bar or swing-arm Upholstered or non-upholstered

[2] NOTE: Phone call was unable to be recorded due to technical reasons

Andy Allen via utoronto.onmicrosoft.com
to Benjamin

Hi Benjamin,

The number of loose chairs is 10,293.

Cheers,
Andy.

Andy Allen
Manager, Academic Scheduling
Academic + Campus Events
University of Toronto
ph: 416-978-6513
www.ace.utoronto.ca

Benjamin Cheng <ben@bcheng.me>
to andy.allen

Hi Andy,

Thanks for getting back to me so quickly. Unfortunately we're in a bit
of a crunch for time. It'd be great if you can just confirm that it's
a problem at the moment, so we can meet to talk specifics on Monday.
Anytime between 12:00 and 13:00 on Monday will work.

Sincerely,
Benjamin Cheng

Andy Allen via utoronto.onmicrosoft.com
to Benjamin

I would say for the most parts it's an annoyance, though in some places it's definitely a problem; we do have more of a problem with specific accommodation furniture being moved/removed.

Andy Allen
Manager, Academic Scheduling
Academic + Campus Events
University of Toronto
McMurrich Building
12 Queen's Park Crescent West
Fourth Floor
Toronto, ON M5S 1S8
ph: 416-978-6513
www.ace.utoronto.ca

[3] Standards Council of Canada, *Degrees of protection provided by enclosures (IP Code)*. 2013.

60529 © IEC:1989+A1:1999
+A2:2013 – 13 –

Element	Numerals or letters	Meaning for the protection of *equipment*	Meaning for the protection of *persons*	Ref.
Code letters	IP	–	–	–
First characteristic numeral	 0 1 2 3 4 5 6	Against ingress of solid foreign objects (non-protected) ≥ 50 mm diameter ≥ 12,5 mm diameter ≥ 2,5 mm diameter ≥ 1,0 mm diameter dust-protected dust-tight	Against access to hazardous parts with (non-protected) back of hand finger tool wire wire wire	Cl. 5
Second characteristic numeral	0 1 2 3 4 5 6 7 8 9	Against ingress of water with harmful effects (non-protected) vertically dripping dripping (15° tilted) spraying splashing jetting powerful jetting temporary immersion continuous immersion High pressure and temperature water jet	–	Cl. 6
Additional letter (optional)	A B C D	–	Against access to hazardous parts with: back of hand finger tool wire	Cl. 7
Supplementary letter (optional)	H M S W	Supplementary information specific to: High voltage apparatus Motion during water test Stationary during water test Weather conditions	–	Cl. 8

[4] US Department of Commerce, *Vehicle Anti-Theft Security System Design. Volume II. Technical Report.*, 1978. Internet: `https://www.ncjrs.gov/pdffiles1/Digitization/74476NCJRS.pdf`.

In Chapter 4 visual conspicuousness was also found to be important. However, there is no simple, objective way of requiring this in a standard. Conspicuousness can best be achieved objectively by judiciously choosing the way in which accessibility is defined.

[5] C. Alfredo. *Complete Part Design Handbook - For Injection Molding of Thermoplastics* Hanser Publishers, 2006.

Types of Polymers	Specific Gravity	Tensile Modulus @ 73 °F (Mpsi)	Tensile Strength @ Yield (Kpsi)	Notch Izod Impact @ 73 °F (ft-lb/in)	Continue Expose Temperature (°F)	Processing Temperature (°F)	Flammability UL-94	Dielectric Strength (Vol/Mil)	Dissipation Factor @ 1.0×10^6 Hz
ABS Unreinforced	1.05	0.30	5.00	2.50 12.00	167 185	410 518	HB	350 500	0.03 0.04
Acrylic Unreinforced	1.17	0.38	7.50	0.03 0.50	150 190	410 575	HB	450 530	0.09
Acetal Unreinforced	1.42	0.400	10.00	1.30	195 230	375 450	HB	560	0.005
HDPE Polyethylene Unreinforced	0.94	0.20	3.50	No Break	158 176	400 535	HB V2	450 500	0.0005
PP Polypropylene Homo Unfilled	0.90	0.17	4.00	0.50 20.00	212	390 525	HB V2	450 600	0.002
PS Polystyrene Unfilled	1.05	0.45	6.00	0.25 0.60	122 158	390 480	HB V2	300 600	0.004 0.0020
PVC Polyvinyl Chloride Rigid	1.38	0.35	5.90	0.40 20.00	150 185	365 400	HB V1	600 800	0.115
PC – 30% Fiber Glass	1.40	1.25	19.00	1.70 3.00	220 265	430 620	V1 V2	450	0.001
PPO – 30% Fiber Glass	1.25	1.10	14.50	1.70 2.30	200 240	520 600	HB V0	550 630	…
PBT – 30% Fiber Glass	1.53	1.35	17.50	0.90	200 250	470 530	HB V0	750	0.004
PET – 30% Fiber Glass	1.67	1.50	22.0	1.60	392	510 565	V0 5V	430	0.002
LCP – 30% Fiber Glass	1.62	2.25	23.00	1.30	430 465	660 680	V0 5V	640 1,000	0.0019
HTN – 30% Fiber Glass @ 73 °F – 50% RH	1.44	1.50	32.00	1.80	315	580 620	V2 V0	500	0.004
Nylon 6/6 – 33% GR @ 73 °F & 50% RH	1.38	0.90	18.00	2.50	265	530 580	HB V2	400	0.006
PEI – 30% Fiber Glass	1.50	1.30	24.50	1.90	356 390	640 800	V0	495 630	0.0025
PPS - 30% Fiber Glass	1.38	1.70	22.0	1.10	390 450	600 750	V0 5V	450	0.0014
PSU – 30% Fiber Glass	1.46	1.35	14.50	1.10	350 375	600 715	V0 5V	450	0.002
DAP – (TS) Fiber Glass	1.94	1.40	7.50	1.00	390 430	290 350	V1 V0	400 450	0.011 0.017
(EP) Epoxy – (TS) Fiber Glass	1.84	3.00	18.00	0.50	350 4450	300 430	HB V0	380 400	0.02 0.05
(PF) Phenolic – (TS) Fiber Glass	1.74 1.88	1.90 2.28	6.50 10.00	0.75 0.90	350 450	330 390	V1 V0	300	0.03
(UP) Polyester – (TS) Fiber Glass	1.75 1.90	1.90 2.00	10.50 15.00	0.50 18.00	200 250	170 320	V0 5V	450 530	0.01 0.04
(PI) Polyimide – (TS) Graphite Fiber	1.65	0.70	7.50	0.70	600 740	690	V0 5V	500 560	0.010 0.003

[6] US Department of Commerce, *Vehicle Anti-Theft Security System Design. Volume II. Technical Report.*, 1978. Internet: `https://www.ncjrs.gov/pdffiles1/Digitization/74476NCJRS.pdf`.

Complexity

The final type of second-tier attack resistance criterion is some defined degree of system complexity. This has been proposed by many previous investigators as a general means of increasing theft deterrence and is, of course, related to several of the other criteria. For example, complexity can increase the time-to-defeat by increasing the number of operations required to mobilize the vehicle. It can impose the requirement for special defeat tools which are either expensive or difficult to improvise. Finally, it can impose the need for a level of knowledge on the thief which is beyond that typically at his disposal. As such, there is no question that complexity can be a valuable tool for the designer in developing an effective anti-theft system. However, unless it is expressed in terms of the subjective time-to-defeat measure, complexity can only be expressed in terms of the specific characteristics of the system. For example, number of moving parts, number of redundant locking functions, number of electronic components, etc., would be typical expressions of complexity. These are, of course, all inherently design-restrictive.

A complexity criterion would tend to preclude a very simple design which effectively reduces the potential attack on the system to a single well-defined method and extends the time required for this method to beyond the 10-minute range. Many designers, including this author, feel that this approach is one of the most promising ones for achieving effective anti-theft designs.

[7] C. Alfredo. *Complete Part Design Handbook - For Injection Molding of Thermoplastics* Hanser Publishers, 2006.

[8] "Engineering Computing Facility (ECF)," Current Engineering Undergraduates. Internet: `https://undergrad.engineering.utoronto.ca/undergrad-resources/engineering-computing-facility-ecf/`.

[9] 

[10] ISO-22448. *Earth-moving machinery – Anti-theft systems – Classification and performance.* 2010.

Table 1 — Summary of system levels

Level	Independent from original control/optional system	Single ECM/ECU	Multiple ECM/ECU	Entry/minimum requirement	Authentication set-up (token, password)
I	No	—	—	Key	—
II	Yes	—	—	Device-specific	—
III	No	—	—	Unique key	—
IV	Yes	—	—	Authentication device	User
V	No	—	—	Authentication device	Manufacturer, manufacturer's dealer, authorized user
VI	No	Yes	No	Authentication device	Manufacturer, manufacturer's dealer
VII	No	No	Yes	Authentication device	Manufacturer, manufacturer's dealer

[11] ISO-180. *Plastics – Determination of Izod impact strength.* 2000.

1.2 The method is used to investigate the behaviour of specified types of specimen under the impact conditions defined and for estimating the brittleness or toughness of specimens within the limitations inherent in the test conditions.

1.3 The method is suitable for use with the following range of materials:

— rigid thermoplastic moulding and extrusion materials, including filled and reinforced compounds in addition to unfilled types; rigid thermoplastics sheets;

— rigid thermosetting moulding materials, including filled and reinforced compounds; rigid thermosetting sheets, including laminates;

— fibre-reinforced thermosetting and thermoplastic composites incorporating unidirectional or non-unidirectional reinforcements such as mat, woven fabrics, woven rovings, chopped strands, combination and hybrid reinforcements, rovings and milled fibres and sheet made from pre-impregnated materials (prepregs);

— thermotropic liquid-crystal polymers.

Table 1 — Summary of system levels

Level	Independent from original control/optional system	Single ECM/ECU	Multiple ECM/ECU	Entry/minimum requirement	Authentication set-up (token, password)
I	No	—	—	Key	—
II	Yes	—	—	Device-specific	—
III	No	—	—	Unique key	—
IV	Yes	—	—	Authentication device	User
V	No	—	—	Authentication device	Manufacturer, manufacturer's dealer, authorized user
VI	No	Yes	No	Authentication device	Manufacturer, manufacturer's dealer
VII	No	No	Yes	Authentication device	Manufacturer, manufacturer's dealer

[12] "Injection molding: The Definitive Engineering Guide". 3D Hubs. Internet: `https://www.3dhubs.com/guides/injection-molding/`.

> Injection molding is widely used today for both consumer products and engineering applications. Almost every plastic item around you was manufactured using Injection molding. This is due to the ability of the technology to produce identical parts at *very high volumes* (typically, 1,000 to 100,000+ units) at a *very low cost per part* (typically, at $1-5 per unit).

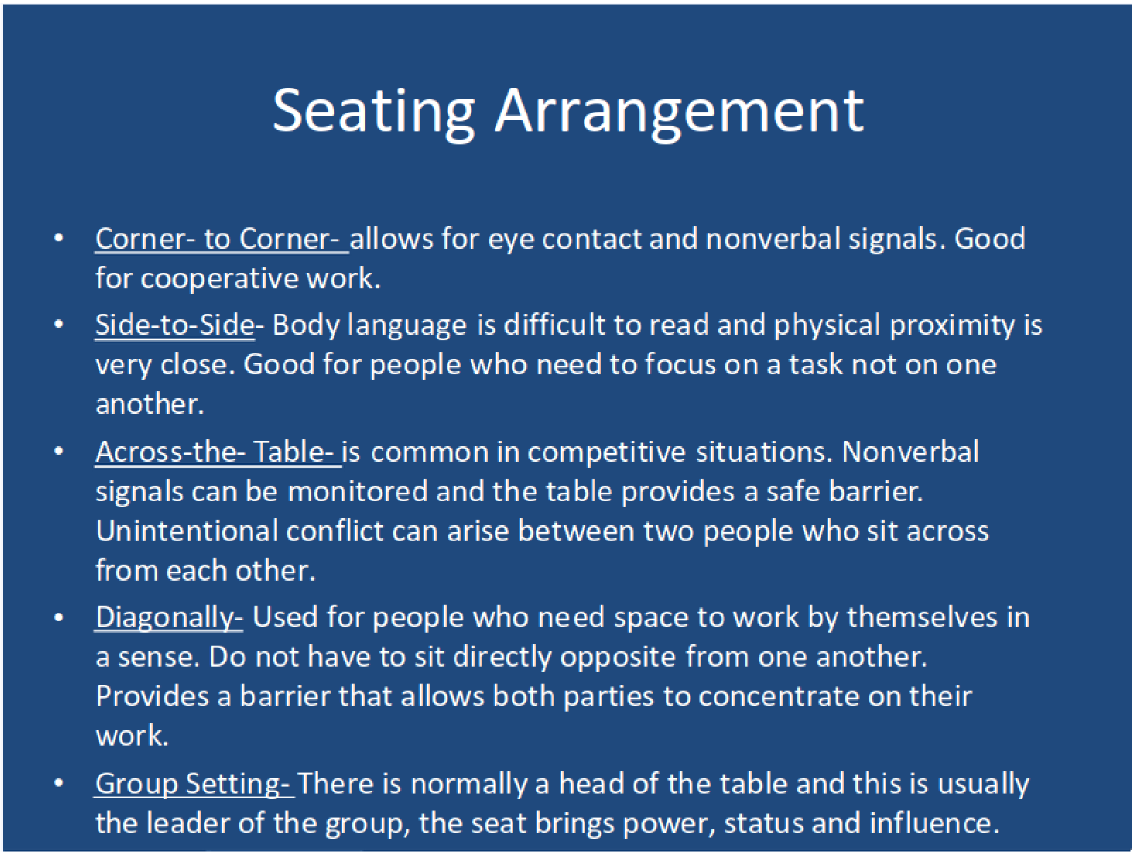
[13] P. Dizikies, "Proximity boosts collaboration on MIT campus," MIT News Office, Internet: `http://news.mit.edu/2017/proximity-boosts-collaboration-mit-campus-0710`.

> That refers to pioneering work by Thomas Allen, a professor emeritus at the MIT Sloan School of Management and author of many studies about workspace. Allen found that collaboration and interaction diminish as a function of distance (in a way that produces a curve when plotted on a graph); even basic conversations are much less likely to occur among workers situated more than 10 meters apart. Many of Allen's ideas are in his 1977 book, "Managing the Flow of Technology."

[14] "Mission," Facilities & Services. Internet: `http://www.fs.utoronto.ca/mission/`.

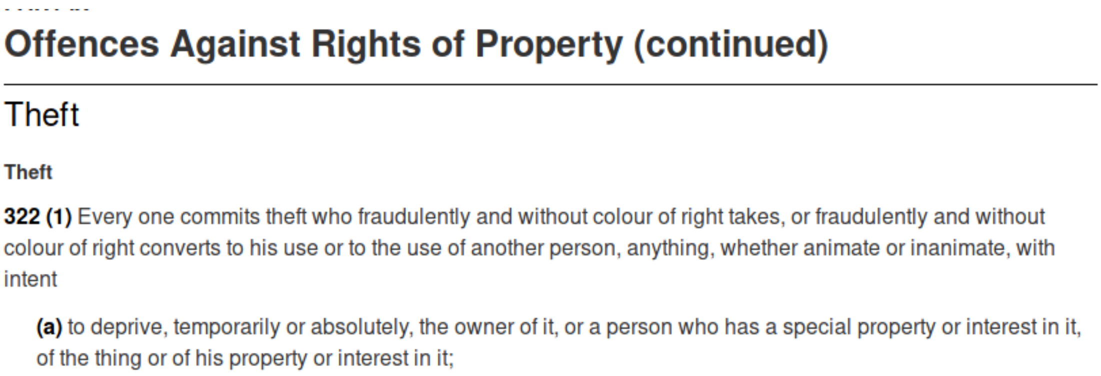
> **Mission**
>
> The F&S Team is at your service!
>
> To facilitate the academic mission of excellence in research and teaching by providing:
>
> - A safe, clean, comfortable, sustainable and attractive environment for the University community
> - Stewardship of the University's physical assets.

[15] "Teamwork and Team Performance." John Wiley and Sons, Inc., Hoboken, New Jersey. Internet: `http://www.wiley.com/college/schermerhorn/0470294418/ppt_student/ch08.ppt`.



[16] S. Kolluru, "Inside the Myhal Centre for Engineering Innovation & Entrepreneurship," The Varsity, Internet: `https://thevarsity.ca/2018/09/13/inside-the-myhal-centre-for-engineering-innovation-entrepreneurship/`.

[17] Canadian Government, *Criminal Code of Canada*, 1985.



Offences Against Rights of Property (continued)

Theft

Theft

322 (1) Every one commits theft who fraudulently and without colour of right takes, or fraudulently and without colour of right converts to his use or to the use of another person, anything, whether animate or inanimate, with intent

> **(a)** to deprive, temporarily or absolutely, the owner of it, or a person who has a special property or interest in it, of the thing or of his property or interest in it;

[18] P. Barrett, F. Davies, Y. Zhang, and L. Barrett. "The impact of classroom design on pupils' learning: final results of a holistic, multi-level analysis". *Building and Environment.* 89, pp. 118-133.

						and far views.
Individualisation	Ownership	K	The degree to which distinct characteristics of the classroom allow a sense of ownership	16	Distinct design features	Originality or novelty character to room. Personalised lockers or coat hooks.
				17	Nature of the display	Child made display.
		L	The degree to which the FF&E are comfortable, supporting the learning and teaching	18	Quality of the furniture, fixture and equipment (FF&E)	Ergonomic and good quality furniture appropriate for age group.
				19	Quality of the chairs and desks	Ergonomic and good quality desks and chairs appropriate for age group.
	Flexibility	M	The degree to which the pupils have an appropriate provision of space	20	Classroom floor area and shape: Key Stage appropriate.	Larger rooms with simpler shapes for older pupils, but more varied plan shapes for younger pupils.
				21	Breakout and storage space attached to the classroom	An attached & dedicated room for breakout and widened corridor for storage.
		N	The degree to which the classroom and wall area allows varied learning methods and activities	22	Learning zones: number of zones key stage appropriate.	A greater number of well-defined zones for play based learning, fewer zones and more formal zones for older pupils.
				23	Wall area for display opportunities	Larger is better.
	Connection	O	The presence of a wide pathway and orienting objects with identifiable destinations	24	Corridor width	Wider is better.
				25	Orienting corridor	Displays, landmarks, and daylight with views towards the outside along the pathway.
Stimulation, Appropriate level of	Complexity	P	The degree to which the classroom provides appropriate visual diversity	26	Visual diversity of layout and ceiling	Curvilinear effect: Overall visual complexity including room layout and displays should be balanced; not too high nor too sterile.
		Q	The degree to which the display provide appropriate visual diversity	27	Visual diversity of display	
	Colour	R	The degree to which the 'colour mood' is appropriate for the learning and teaching	28	Wall colour and area	Light/white walls with bright highlights or feature wall.
				29	Colours of blinds, carpet, chairs& desks	Bright colour works better.
				30	Display colour	Bright colour works better.

[19] "Set of average weights for furniture, appliances and other items." Internet: `https://democracy.york.gov.uk/documents/s2116/`.

Office Furniture	Filing cabinet, large	50
Office Furniture	Office Chair	12
Office Furniture	Office Desk	25

[20] C. Alfredo. *Complete Part Design Handbook - For Injection Molding of Thermoplastics* Hanser Publishers, 2006.

Thermoplastic elastomer (TPE) resins are rubbery materials with the characteristics of a thermoplastic and the performance properties of a thermoset rubber. TPEs are processed using the same thermoplastic equipment and methods, such as extrusion, injection molding, and blow molding.

[21] C. Vasile, and M. Pascu. *Practical Guide to Polyethylene Practical Guide to Polyethylene.* Rapra Technology Limited, 2005, pp. 4-6

1.2 Strengths

PE is used more than any other thermoplastic polymer. There is a wide variety of grades and formulations available that have an equally wide range of properties. In general, the outstanding characteristics of PE are toughness, ease of processing, chemical resistance, abrasion resistance, electrical properties, impact resistance, low coefficient of friction, and near-zero moisture absorption.

1.5 Applications

The applications of plastics in general and of PE in particular are innumerable. The main applications of PE are summarised in **Figure 1.3** and **Table 1.3**.

The consumption of LDPE at the European level is 4.7 million tonnes, of which film accounts for 60%. Co-extruded film permits a reduction in film thickness for the same mechanical resistance.

LDPE is mainly used as film (59%), extrusion coating (17%), injection moulding (6%), wire and cable (4%), adhesives and sealants (4%), sheets (2%), blow moulding (1%), and miscellaneous, including pipe, conduit, and rotomoulding (7%). There are also increasing demands for PE use in the medical field (growing demand for sterile packaging), the automotive sector (HDPE automotive fuel tanks is a booming business), cosmetics (innovative packaging designs), liquid food packaging, and twin-sheet thermoformed HDPE pallets to replace wooden pallets. HDPE is also used in pipes for canalisation (17%), injection moulded products (20%), industrial containers, packaging, housewares, and so on.

[22] V. Thukur, M. Thukur, A. Pappu. *Hybrid Polymer Composite Materials - Properties and Characterisation.* Elsevier, 2017, pp. 48.

2.4.5 Polyvinyl chloride

PVC can be polymerized industrially by emulsion or suspension polymerization techniques. Its light weight, good mechanical strength, and toughness are key technical advantages for building and construction. Other properties of importance are resistance to weathering, chemical rotting, corrosion, shock, and abrasion. PVC is an excellent material in electrical applications for sheathing of cables. It performs better in terms of combustibility, flammability, flame propagation, and heat release compared with other plastics. PVC is the material of choice for scaffolding billboards, interior design articles, window frames, and fresh and waste water systems. Chlorinated PVC is ideally suitable for self-supporting constructions where good corrosion resistance at high temperatures is needed.

[23] W. Becker, T. Shipley, J. Roch. *ASM Handbook, Volume 11 - Failure Analysis and Prevention.* ASM International, 2008.

[24] "The Eleven Most Important Types of Plastic." Internet: `https://www.creativemechanisms.com/blog/eleven-most-important-plastics` [July 21, 2016].

11. ABS (Acrylonitrile Butadiene Styrene):

ABS has a strong resistance to corrosive chemicals and physical impacts. It is very easy to machine, is readily available and has a low melting temperature making it particularly simple to use in injection molding manufacturing processes or 3D printing.

LEGO toys made from ABS plastic

Four short phrases to describe the major benefits of ABS relative to other plastics and materials would be:

- Impact Resistant
- Readily Available
- Simple To Manufacture
- #1 Material For 3D Printing

[25] D. Niessner. *Practical Guide to Structures, Properties and Applications of Styrenic Polymers.* Smithers Rapra Technology, 2013, pp. 8.

- Acrylonitrile-butadiene-styrene copolymer (ABS): is an opaque, ductile and stiff thermoplastic polymer with a broad processing window, which is strong and durable even at low temperatures, with good resistance to heat and chemicals.

[26] M. Kutz. *Applied Plastics Engineering Handbook - Processing, Materials, and Applications.* (2nd Edition). Elsevier, 2017, pp. 7.

combination of properties and processing versatility have made PCs the ideal resin for many applications. In addition, transparency gave polycarbonates another dimension and has led to applications in safety glazing, light covers, automotive headlamp lenses, water bottles, compact discs, and ophthalmic applications.

[27] M. Kutz. *Applied Plastics Engineering Handbook - Processing, Materials, and Applications.* (2nd Edition). Elsevier, 2017, pp. 4.

Polyamides was a new concept in plastics for several reasons. It was semicrystalline polymer that underwent a sharp transition from solid to melt. In addition, it had a relatively high service temperature. The combination of toughness, rigidity, and "lubrication-free" performance made PA66 peculiarly suited for mechanical bearing and gear applications. Polyamides acquired the reputation of a quality material by showing that a thermoplastic could be tough, as well as stiff, and perform better than metals in some cases. This performance gave nylon the label "an engineering thermoplastic."

[28] M. Ashby, and K. Johnson. *Materials and Design - The Art and Science of Material Selection in Product Design.* (2nd Edition). Elsevier, 2010, pp. 216.

Polyethylene (PE)

What Is It? Polyethylene $(CH_2)n$, first synthesized in 1933, looks like the simplest of molecules, but the number of ways in which the $-CH_2-$ units can be linked is large. It is the first of the polyolefins, the bulk thermoplastic polymers that account for a dominant fraction of all polymer consumption. Polyethylene is inert, and extremely resistant to fresh and salt water, food, and most water-based solutions. Because of this it is widely used in household products and food containers.

Design Notes PE is commercially produced as film, sheet, rod, foam and fiber. Drawn PE fiber has exceptional mechanical stiffness and strength, exploited in geo-textile and structural uses. Polyethylene is cheap, and particularly easy to mold and fabricate. It accepts a wide range of colors, can be transparent, translucent or opaque, has a pleasant, slightly waxy feel, can be textured or metal coated, but is difficult to print on. PE is a good electrical insulator with low dielectric loss, so suitable for containers for microwave cooking.

Typical Uses Oil containers, street bollards, milk bottles, toys, beer crates, food packaging, shrink wrap, squeeze tubes, disposable clothing, plastic bags, Tupperware, chopping boards, paper coatings, cable insulation, artificial joints, and as fibers – low cost ropes and packing tape reinforcement.

Competing Materials Polypropylene, polystyrene, ABS, SAN, EVA, elPVC; aluminum as foil and packaging; steel sheet as cans.

The Environment PE is FDA compliant – indeed it is so non-toxic that it can be embedded in the human body (heart valves, hip-joint cups, artificial artery). PE, PP and PVC are made by processes that are relatively energy-efficient, making them the least energy-intensive of commodity polymers. PE can be produced from renewable resources – from alcohol derived from the fermentation of sugar or starch, for instance. Its utility per kilogram far exceeds that of gasoline or fuel-oil, so that production from oil will not disadvantage it in the near future. Polyethylene is readily recyclable if it has not been coated with other materials, and – if contaminated – it can be incinerated to recover the energy it contains.

Technical Notes Low density polyethylene (LDPE), used for film and packaging, has branched chains which do not pack well, making it less dense than water. Medium (MDPE) and high (HDPE) density polyethylenes have longer, less branched chains, making them stiffer and stronger; they are used for containers and pipes. Linear low density polyethylene (LLPDE) is less resistant to organic solvents, but even this can be overcome by converting its surface to a fluoro-polymer by exposing it to fluorine gas. Treated in this way (when it is known as "Super PE") it can be used for petrol tanks in cars and copes with oil, cleaning fluid, cosmetics and that most corrosive of substances: cola concentrate. Very low density polyethylene (VLDPE) is similar to EVA and plasticized PVC.

Attributes of Polyethylene

Price, \$/kg	1.10–4.00
Density, Mg/m³	0.92–1.4

Technical Attributes

El. modulus, GPa	0.03–1.4
Elongation, %	10–1400
Fr. toughness, MPa·m$^{1/2}$	0.40–5.16
Vickers hardness, H_v	5–8
Yld. strength, MPa	8–31
Service temp., C	-40–100
Specific heat, J/kg·K	1559–1916
Th. conduct., W/m·K	0.12–0.50
Th. expansion, 10^{-6}/K	106–450

Eco-Attributes

Energy content, MJ/kg	104–114
Recycle potential	High

Aesthetic Attributes

Low (0), High Pitch (10)	3–7
Muffled (0), Ringing (10)	1–3
Soft (0), Hard (10)	5–7
Warm (0), Cool (10)	4–5
Gloss, %	5–136

Features (Relative to Other Polymers)

Easily molded
Durable
Low cost

[29] M. Ashby, and K. Johnson. *Materials and Design - The Art and Science of Material Selection in Product Design.* (2nd Edition). Elsevier, 2010, pp. 217.

Polyvinylchloride (PVC)

What Is It? PVC – Vinyl – is one of the cheapest, most versatile and – with polyethylene – the most widely used of polymers and epitomizes their multi-faceted character. In its pure form – as a thermoplastic, tpPVC – it is rigid, and not very tough; its low price makes it a cost-effective engineering plastic where extremes of service are not encountered. Incorporating plasticizers creates flexible PVC, elPVC, a material with leather-like or rubber-like properties and used a substitute for both. By contrast, reinforcement with glass fibers gives a material that is sufficiently stiff, strong and tough to be used for roofs, flooring and building panels. Both rigid and flexible PVC can be foamed to give lightweight structural panels, and upholstery for cars and domestic use. Blending with other polymers extends the range of properties further: vinyl gramophone records were made of a vinyl chloride/acetate co-polymer; blow molded bottles and film are a vinyl chloride/acrylic co-polymer.

Design Notes In its pure form, PVC is heavy, stiff and brittle. Plasticizers can transform it from a rigid material to one that is almost as elastic and soft as rubber. Plasticized PVC is used as a cheap substitute for leather, which it can be made to resemble in color and texture. It is less transparent than PMMA or PC, but it also costs much less, so it is widely used for transparent, disposable containers. PVC is available as film, sheet or tube. It can be joined with polyester, epoxy or polyurethane adhesives. It has excellent resistance to acids and bases and good barrier properties to atmospheric gases, but poor resistance to some solvents.

Typical Uses tpPVC: pipes, fittings, profiles, road signs, cosmetic packaging, canoes, garden hoses, vinyl flooring, windows and cladding, vinyl records, dolls, medical tubes. elPVC: artificial leather, wire insulation, film, sheet, fabric, car upholstery.

Competing Materials Polyethylene and polypropylene, PTFE for high performance roofing.

The Environment The vinyl chloride monomer is thoroughly nasty stuff, leading to pressure to discontinue production. But properly controlled, the processing is safe, and the polymer PVC has no known harmful effects. Disposal, however, can be a problem: thermal degradation releases chlorine, HCl and other toxic compounds, requiring special high temperature incineration for safety.

Technical Notes PVC can be a thermoplastic or a thermoset. There are many types of PVC: expanded rigid PVC, type I, type II, CPVC, acrylic/PVC blend, clear PVC.

Attributes of PVC

Price, \$/kg	1.00–1.20
Density, Mg/m^3	1.3–1.58

Technical Attributes

El. modulus, GPa	2.14–4.14
Elongation, %	11.93–80
Fr. toughness, MPam$^{1/2}$	1.46–5.12
Vickers hardness, H_v	10–15
Yld. strength, MPa	35.4–52.1
Service temp., C	-20–70
Specific heat, J/kg·K	1355–1445
Th. conduct., W/m·K	0.15–0.29
Th. expansion, 10^{-6}/K	1.8–180

Eco-Attributes

Energy content, MJ/kg	77–83
Recycle potential	High

Aesthetic Attributes

Low (0), High Pitch (10)	6–7
Muffled (0), Ringing (10)	4
Soft (0), Hard (10)	7
Warm (0), Cool (10)	4–5

Features (Relative to Other Polymers)

Corrosion resistant
Low cost
Resilient

[30] M. Ashby, and K. Johnson. *Materials and Design - The Art and Science of Material Selection in Product Design.* (2nd Edition). Elsevier, 2010, pp. 209.

Acrylonitrile-butadiene-styrene (ABS)

What Is It? ABS is tough, resilient, and easily molded. It is usually opaque, although some grades can now be transparent, and it can be given vivid colors. ABS-PVC alloys are tougher than standard ABS and, in self-extinguishing grades, are used for the casings of power tools.

Design Notes ABS has the highest impact resistance of all polymers. It takes color well. Integral metallics are possible (as in GE Plastics' Magix). ABS is UV resistant for outdoor application if stabilizers are added. It is hygroscopic (may need to be oven dried before thermoforming) and can be damaged by petroleum-based machining oils. ASA (acrylic-styrene-acrylonitrile) has very high gloss; its natural color is off-white but others are available. It has good chemical and temperature resistance and high impact resistance at low temperatures. UL-approved grades are available. SAN (styrene-acrylonirtile) has the good processing attributes of polystyrene but greater strength, stiffness and chemical and heat resistance. By adding glass fiber the rigidity can be increased dramatically. It is transparent (over 90% in the visible range but less for UV light) and has good color. Depending on the amount of acrylonitrile that is added this can vary from water white to pale yellow, but without a protective coating, sunlight causes yellowing and loss of strength, slowed by UV stabilizers. All three can be extruded, compression molded or formed to sheet that is then shaped by vacuum thermoforming. They can be joined by ultra-sonic or hot-plate welding, or bonded with polyester, epoxy, isocyanate or nitrile-phenolic adhesives.

Typical Uses ABS: cases for computers and TVs, telephones, food mixers, vacuum cleaners, baths, shower trays, pipes, luggage shells, RV parts, shower stalls, cassette holders, automotive parts, safety hard hats, Legos, computer mice, razors, handles, shavers, chairs. SAN: telephone cases, food processing bowls, medical syringes, mixing bowls, beakers, coffee filters, cassettes, industrial battery cases, toothbrushes, cosmetic packs, dinnerware, food containers. ASA: appliance panels and knobs, toys, medical instruments, rear view mirrors, garden tables and chairs, hose fittings, garden tools, letter boxes, boat shells, windsurfing boards.

Competing Materials High density polyethylene, polypropylene, butyl rubber, nylon.

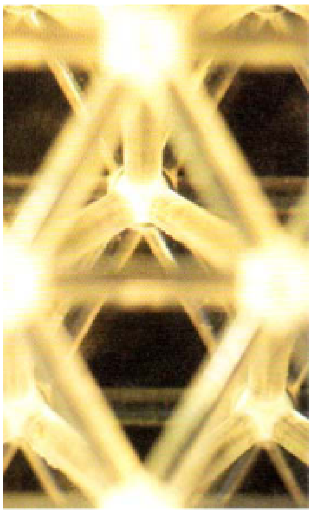
The Environment The acrylonitrile monomer is nasty stuff, almost as poisonous as cyanide. Once polymerized with styrene it becomes harmless. Some grades of ABS are FDA compliant and can be recycled.

Technical Notes ABS is a terpolymer – one made by co-polymerizing three monomers: acrylonitrile, butadiene and styrene. The acrylonitrile gives thermal and chemical resistance, rubber-like butadiene gives ductility and strength, the styrene gives a glossy surface, ease of machining and a lower cost. In ASA, the butadiene component (which gives poor UV resistance) is replaced by an acrylic ester. Without the addition of butyl, ABS becomes SAN – a similar material with lower impact resistance and toughness.

Attributes of ABS	
Price, $/kg	1.50–2.80
Density, Mg/m^3	1.01–1.21
Technical Attributes	
El. modulus, GPa	1.1–2.9
Elongation, %	1.5–100
Fr. toughness, MPa·m$^{1/2}$	1.2–4.2
Vickers hardness, H_v	6–15
Yld. strength, MPa	18.5–51
Service temp., C	-18–90
Specific heat, J/kg·K	1386–1919
Th. conduct., W/m·K	0.18–0.33
Th. expansion, 10^{-6}/K	84.6–234
Eco-Attributes	
Energy content, MJ/kg	95–104
Recycle potential	Medium
Aesthetic Attributes	
Low (0), High Pitch (10)	6–7
Muffled (0), Ringing (10)	3–4
Soft (0), Hard (10)	6–7
Warm (0), Cool (10)	4–5
Gloss, %	10–96

Features (Relative to Other Polymers)
Durable and tough
Readily colored
Easily molded

[31] M. Ashby, and K. Johnson. *Materials and Design - The Art and Science of Material Selection in Product Design.* (2nd Edition). Elsevier, 2010, pp. 212.



Polycarbonate (PC)

What Is It? PC is one of the "engineering" thermoplastics, meaning that it has better mechanical properties than the cheaper "commodity" polymers. The family includes the plastics polyamide (PA), polyoxymethylene (POM) and polytetrafluorethylene (PTFE). The benzene ring and the -OCOO- carbonate group combine in pure PC to give it its unique characteristics of optical transparency and good toughness and rigidity, even at relatively high temperatures. These properties make PC a good choice for applications such as compact disks, safety hard hats and housings for power tools. To enhance the properties of PC even further, it is possible to co-polymerize the molecule with other monomers (improves the flame retardancy, refractive index and resistance to softening), or to reinforce the PC with glass fibers (giving better mechanical properties at high temperatures).

Design Notes The optical transparency and high impact resistance of PC make it suitable for bullet-resistant or shatter-resistant glass applications. It is readily colored. PC is usually processed by extrusion or thermoforming (techniques that impose constraints on design), although injection molding is possible. When designing for extrusion with PC, the wall thickness should be as uniform as possible to prevent warping, and projections and sharp corners avoided – features like hollows and lone unsupported die sections greatly increase the mold cost. The stiffness of the final part can be improved by the incorporation of corrugations or embossed ribs. PC can be reinforced using glass fibers to reduce shrinkage problems on cooling and to improve the mechanical performance at high temperatures. It can be joined using adhesives, fasteners or welding.

Typical Uses Compact disks, housings for hair dryers, toasters, printers and power tool housings, refrigerator linings, mechanical gears, instrument panels, motorcycle helmets, automotive bumpers and body parts, riot shields.

Competing Materials Acetal, acrylic and polyester.

The Environment The processing of engineering thermoplastics requires a higher energy input than that of commodity plastics, but otherwise there are no particular environmental penalties. PC can be recycled if unreinforced.

Technical Notes The combination of the benzene ring and carbonate structures in the PC molecular structure give the polymer its unique characteristics of high strength and outstanding toughness. PC can be blended with ABS or polyurethane. ABS/PC gets its flame retardance and UV resistance from polycarbonate at a lower cost than that of ABS. PU/PC gets its rigidity from polycarbonate and flexibility and ease of coating from polyurethane.

Attributes of Polycarbonate	
Price, \$/kg	3.80–4.30
Density, Mg/m^3	1.14–1.21
Technical Attributes	
El. modulus, GPa	2.21–2.44
Elongation, %	70–150
Fr. toughness, MPa·m$^{1/2}$	2.1–4.602
Vickers hardness, H_v	17–22
Yld. strength, MPa	59.1–69
Service temp., C	-40–120
Specific heat, J/kg·K	1535–1634
Th. conduct., W/m·K	0.19–0.22
Th. expansion, 10^{-6}/K	120.1–136.8
Eco-Attributes	
Energy content, MJ/kg	120–130
Recycle potential	High
Aesthetic Attributes	
Low (0), High Pitch (10)	7
Muffled (0), Ringing (10)	4
Soft (0), Hard (10)	7
Warm (0), Cool (10)	4–5

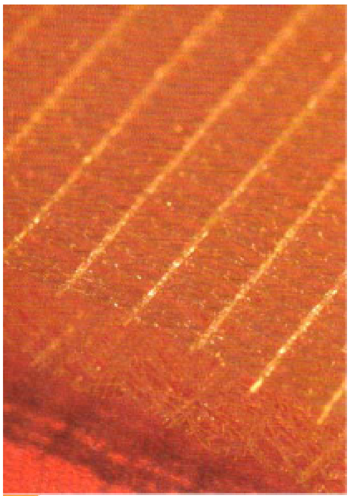
Features (Relative to Other Polymers)

Optically clear

Strong

Tough

[32] M. Ashby, and K. Johnson. *Materials and Design - The Art and Science of Material Selection in Product Design.* (2nd Edition). Elsevier, 2010, pp. 210.



Polymers

Polyamide (PA), Nylon

What Is It? Back in 1945, the war in Europe just ended, the two most prized luxuries were cigarettes and nylons. Nylon (PA) can be drawn to fibers as fine as silk, and was widely used as a substitute for it. Today, newer fibers have eroded its dominance in garment design, but nylon-fiber ropes, and nylon as reinforcement for rubber (in car tires) and other polymers (PTFE, for roofs) remains important. It is used in product design for tough casings, frames and handles, and – reinforced with glass – as bearings gears and other load-bearing parts. There are many grades (Nylon 6, Nylon 66, Nylon 11,...) each with slightly different properties.

Design Notes Nylons are tough, strong and have a low coefficient of friction. They have useful properties over a wide range of temperature (-80–120 C). They are easy to injection mold, machine and finish, can be thermally or ultrasonically bonded, or joined with epoxy, phenol-formaldehyde or polyester adhesives. Certain grades of nylon can be electroplated allowing metallization, and most accept print well. A blend of PPO/nylon is used in fenders, exterior body parts. Nylon fibers are strong, tough, elastic and glossy, easily spun into yarns or blended with other materials. Nylons absorb up to 4% water; to prevent dimensional changes, they must be conditioned before molding, allowing them to establish equilibrium with normal atmospheric humidity. Nylons have poor resistance to strong acids, oxidizing agents and solvents, particularly in transparent grades.

Typical Uses Light duty gears, bushings, sprockets and bearings; electrical equipment housings, lenses, containers, tanks, tubing, furniture casters, plumbing connections, bicycle wheel covers, ketchup bottles, chairs, toothbrush bristles, handles, bearings, food packaging. Nylons are used as hot-melt adhesives for book bindings; as fibers – ropes, fishing line, carpeting, car upholstery and stockings; as aramid fibers – cables, ropes, protective clothing, air filtration bags and electrical insulation.

Competing Materials Polypropylene, polyester and ABS.

The Environment Nylons have no known toxic effects, although they are not entirely inert biologically. Nylons are oil-derivatives, but this will not disadvantage them in the near future. With refinements in polyolefin catalysis, nylons face stiff competition from less expensive polymers.

Technical Notes The density, stiffness, strength, ductility and toughness of nylons all lie near the average for unreinforced polymers. Their thermal conductivities and thermal expansion are a little lower than average. Reinforcement with mineral, glass powder or glass fiber increases the modulus, strength and density. Semi-crystalline nylon is distinguished by a numeric code for the material class indicating the number of carbon atoms between two nitrogen atoms in the molecular chain. The amorphous material is transparent, the semi-crystalline material is opal white.

Attributes of Nylon	
Price, \$/kg	2.90–11.50
Density, Mg/m^3	1–1.42
Technical Attributes	
El. modulus, GPa	0.67–4.51
Elongation, %	4–1210
Fr. toughness, MPa·m$^{1/2}$	0.58–8.03
Vickers hardness, H_v	6–28
Yld. strength, MPa	20.7–101.6
Service temp., C	-80–120
Specific heat, J/kg·K	1421–2323
Th. conduct., W/m·K	0.18–0.35
Th. expansion, 10^{-6}/K	50.4–216
Eco-Attributes	
Energy content, MJ/kg	110–120
Recycle potential	Medium
Aesthetic Attributes	
Low (0), High Pitch (10)	6–7
Muffled (0), Ringing (10)	3–4
Soft (0), Hard (10)	6–7
Warm (0), Cool (10)	4–5
Gloss, %	65–150

Features (Relative to Other Polymers)
Strong
Tough
Durable

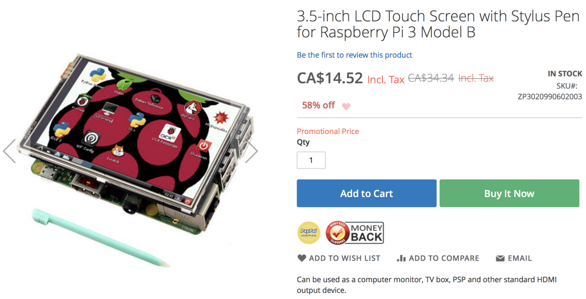
[33] Centers for Disease Control and Prevention. *Why are discipline and consquences important?*. Internet: https://www.cdc.gov/parents/essentials/consequences/whyimportant.html.

Negative consequences let your child know you do not like what she has done. Your child is less likely to repeat the behavior when you use negative consequences. Negative consequences are also called discipline. Negative consequences include things like ignoring, distraction, loss of a privilege, and time-out. Use negative consequences for behaviors you would like your child to stop. It's a good idea to start with ignoring and distraction, especially for young children. Other consequences may be needed if ignoring and distraction don't work or are not possible. Natural consequences, delay or removal of privileges, and time-out can be used to stop misbehavior. More information about these consequences is provided below.

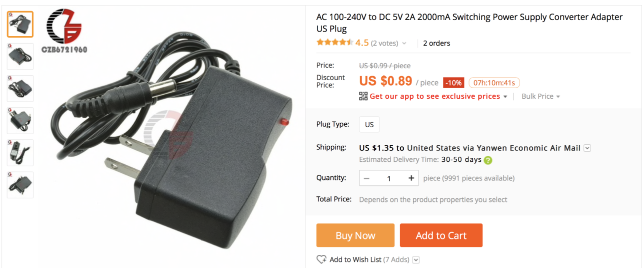
[34] J. Sivadjian, D. Ribeiro. "Comparative Studies on the Permeability to Water and to Water Vapor of Plastic Materials by the Hygrophotographic Technique". *Journal of Applied Polymer Science*, 8, pp. 1043-1413.

[35] M. Gilbert. *Brydson's Plastics Materials* (8th Edition), 2017, Elsevier.

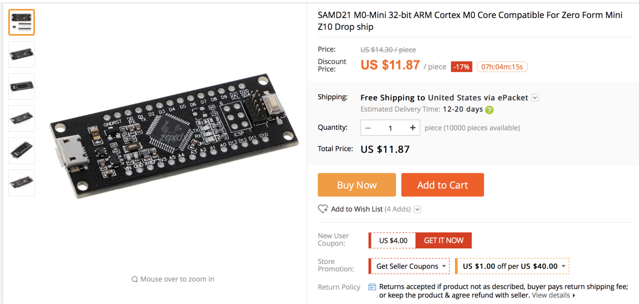
[36] Zapals. Internet: `https://www.zapals.com/raspberry-pi-3-model-b-3-5-inch-lcd-touch-screen-with-stylus-pen-hd-1920x1080.html`.



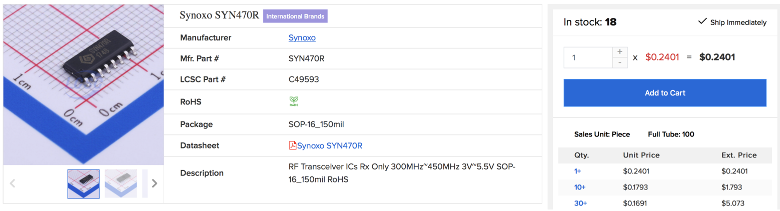
[37] AliExpress. Internet: `https://www.aliexpress.com/item/AC-100-240V-to-DC-5V-2A-2000mA-Switching-Power-Supply-Converter-Adapter-US-Plug/32661794396.html`



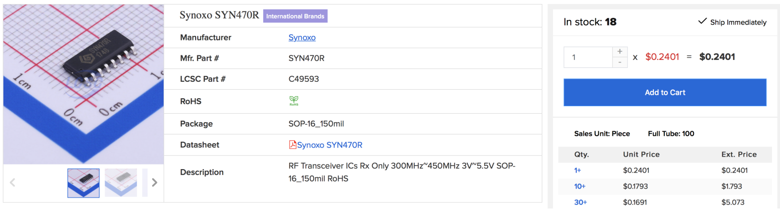
[38] AliExpress. Internet: `https://www.aliexpress.com/item/SAMD21-M0-Mini-32-bit-ARM-Cortex-M0-Core-Compatible-For-Zero-Form-Mini-Z10-Drop/32891399951.html`



[39] LCSC. Internet: https://lcsc.com/product-detail/RF-Transceiver-ICs_Synoxo_SYN470R_Synoxo-SYN470R_C49593.html

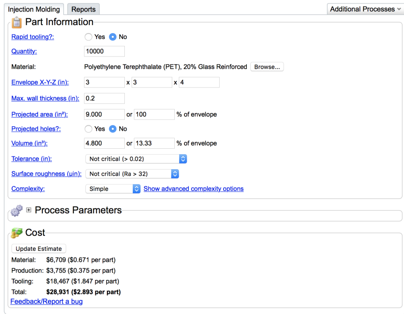


[40] AliExpress. Internet: https://www.aliexpress.com/item/USB-Universal-Magnetic-Card-Barcode-Reader-Stripe-Bidirectional-MSR-Card-Reader-POS-Reader-1-2-track/32783891694.html?spm=2114.search0204.8.10.356d7d2bl6oXVk

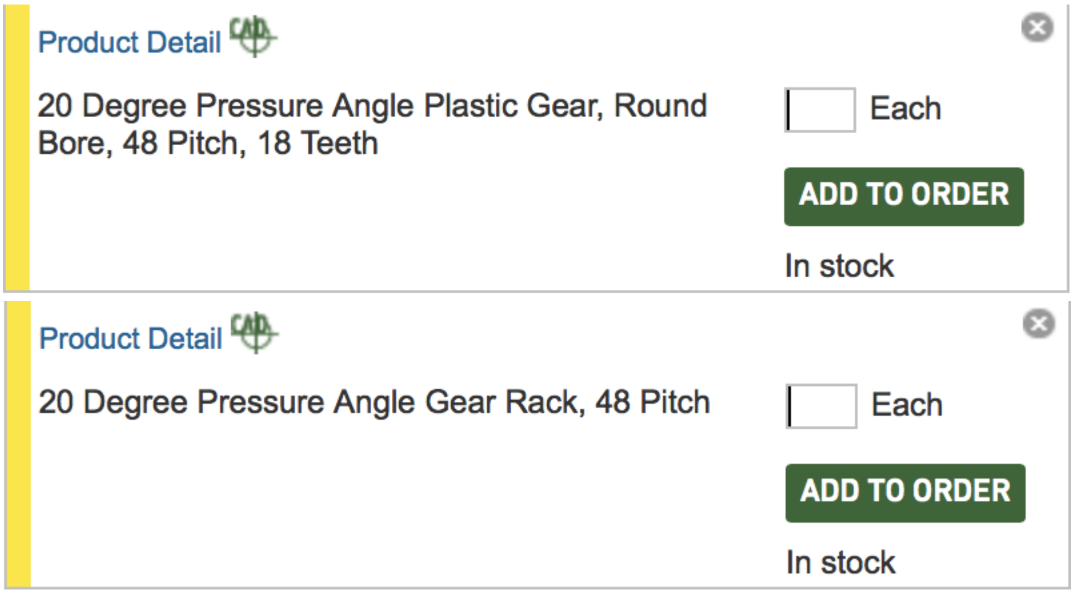


[41] AliExpress. Internet: https://www.aliexpress.com/item/Micro-130-pony-up-to-four-drive-dc-motor-small-motor-production-of-3V/32863474423.html

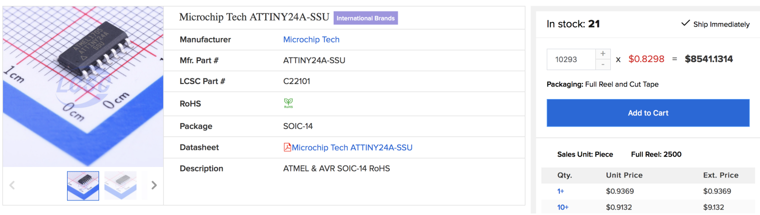
[42] Custompart.net. *Injection Molding Cost Estimator*. Internet: https://www.custompartnet.com/estimate/injection-molding/.



[43] McMaster-Carr. *Gears — McMaster-Carr*. Internet: https://www.mcmaster.com/gears.



[44] LCSC. Internet: https://lcsc.com/product-detail/ATMEL-AVR_MICROCHIP_ATTINY24A-SSU_ATTINY24A-SSU_C22101.html.



13 Original Design Brief

The original design brief is included here for convenience.

Improving Collaborative Furniture in Myhal
ESC 101
Due Date: 2018-10-27

Background

The Myhal Centre for Engineering Innovation and Entrepreneurship (CEIE) aims to "facilitate multidisciplinary collaboration to the fullest," boasting "collaborative spaces." [1] In this design brief, we aim to outline the design of improved collaboration furniture to streamline and facilitate this goal, in particular, chairs and improving the retention rate, ergonomics and collaborative aspects of this furniture.

In the Lee and Margaret Lau Auditorium (MY150), there are two types of chairs available, which share the same physical seat but differ in their method of movement relative to the ground. The first type is a swivel chair[2], similar to an office chair, while the other is a seat attached by an arm to the table[3]. Using the requirements as defined below, the current chairs limit collaboration while providing a unacceptable ergonomic experience. Furthermore, the swivel chairs mentioned above can be easily stolen as the auditorium can be entered at one's leisure. A recommendation must fulfill certain requirements, in particular the chairs must allow a certain degree of motion while preventing larceny, should be cost-effective as compared to the current chairs, and should provide a seating experience that considers human factors.

Who Cares About Better Chairs?

Students Seated in the Lee and Margaret Lau Auditorium

The primary users of the seats in the Lee and Margaret Lau Auditorium in the Myhal CEIE are the students to be seated in them. As the primary users, these students are to be considered the primary stakeholder. These students include Engineering Science students, which is itself a superset of Engineering Science commuters.

University of Toronto Facilities and Services Staff

Part of the goal of the Facilities and Services team is to "provide a safe, clean, comfortable, sustainable and attractive environment for the University community" [12]. As such, the caretaking staff are required to clean in and around the selected furniture and have an interest in the selection made.

Professors and TAs

Professors and TAs who teach in the room have a vested interest in the effective collaboration of students, which is the goal of this design brief.

The Direct Sponsors of the MCEIC

The entities paying for the Myhal CEIE have an interest in fulfilling the mission goal: "[facilitating] multidisciplinary collaboration". "Direct sponsors" are the entities to be responsible for the expenditure of Myhal, namely the University, the Faculty of Applied Science and Engineering, and/or Sponsors (e.g. Lee and Margaret Lau).

High Level Objective

Fulfill the goal of the Myhal CEIE by means of augmenting and supporting collaboration with improved furniture, while preventing chair misplacement and/or larceny.

Detailed Objectives

1. Actively prevent removal from its designated position.
2. Be of reasonable size. If the chairs are bulky, then their functionality will decrease. This may be due to a variety of reasons- the large size may prevent mobility or just the overall convenience of the chair. This sizing must also be in accordance with fire safety codes. This is in the interest of all stakeholders.
3. Reduce cost if possible. The cost is not a massive factor if the theft prevention is acceptable, as the seating devices will not require as much replacement. The direct sponsors have an interest in reducing the amount of money spent on improving the Myhal Centre.
4. Be of reasonable weight; the chair should be easy to move and use.
5. Improve ergonomic design of chair. The chair should be comfortable for normal use.
6. Improve collaboration by facilitating free movement of chairs. By allowing a large range of motion, students are able relocate to meet their desired seating arrangement, which is important to effective collaboration [13], as per the high level objective.

Metrics for Proper Chair Design

1. **Metric for Theft Prevention**: Does the chair include a dedicated anti-theft measure which cannot be circumvented without damage to the rest of the chair?

2. **Metric for Dimensions**: Measure dimensions as specified in ISO-5970:1979. The measured dimensions are rated in accordance to the sizemark in the above standard. The sizemarks are defined in Table 1.

Dimensions in millimetres

Identification		Sizemark	0[1]	1	2	3	4	5	6
		Colour	white	orange	violet	yellow	red	green	blue
Reference stature — average body height			900	1 050	1 200	1 350	1 500	1 650	1 800
h_5	Height of seat[2] (tolerance ± 10)		220	260	300	340	380	420	460
t_4	Effective depth of seat[3] (tolerance ± 10)		–	260	290	330	360	380	400
b_3	Minimum width of seat		–	250	270	290	320	340	360
W	Reference point for β[4]		–	160	170	190	200	210	220
h_6	Maximum height to bottom of backrest[5][6]		–	120	130	150	160	170	190
h_7	Height to top of backrest[6]	min.	–	210	250	280	310	330	360
		max.	–	250	280	310	330	360	400
b_4	Minimum width of backrest[7]		–	250	250	250	280	300	320
r_1	Radius of front edge of the seat[8]		–	30 to 50	30 to 50	30 to 50	30 to 50	30 to 50	30 to 50
r_2	Minimum radius of backrest[9]		–	300	300	300	300	300	300
δ	Angle of seat[10]		–	0° to 4°	0° to 4°	0° to 4°	0° to 4°	0° to 4°	0° to 4°
β	Inclination of backrest[11]		–	95° to 106°	95° to 106°	95° to 106°	95° to 106°	95° to 106°	95° to 106°

Table 1: Sizemark Definitions (image from ISO-5970:1979 document). Citations within the table are to the document's references.

3. **Metric for Weight**: The weight of the components of the chair is measured and compiled to find the total weight.

4. **Metric for Ergonomics**: Rate the chair using Table 2 for ergonomics (adapted from ISO 9241-5:1998) and count the number of attributes satisfied.

5. **Metric for Cost**: Determine the cost of the chair components and associated systems (CAD), and add them to the cost of the labor to assemble and install such a system.

6. **Metric for Teamwork**: Measure the lateral clearance of the chair. Lateral clearance here is defined as the distance that the chair is able to freely move. If the lateral clearance is greater than 10 metres, further measurement is not required. After 10 metres, the communication can no longer be considered in-person [7].

7. **Metric for Strength and Durability**: The durability and usability of the chair must theoretically withstand the following ISO durability test standards [14].

Attribute	Y/N
Seat Height Adjustment - You should be able to adjust your seat height so that your knees are a little lower than your hips, with your feet resting flat on the floor.	
Seat Pan Depth Adjustment - This allows you to adjust the depth of your seat so that you have 1-4 inches between the front edge of your seat and the back of your knee to allow for both leg support and blood flow.	
Backrest Height Adjustment - The ability to adjust the height of your chair back allows you to position the contours of the back cushion for optimal back support.	
Swivel Base - Provides the ability to turn while seated.	
Back Angle Adjustment - This allows you to fine tune the back for a comfortable position. We recommend you change positions throughout the day or leave the back angle unlocked and rock back and forth.	
Back Tilt Tension Adjustment - The tension knob lets you adjust the pressure needed to rock back in your chair.	
Arm Support Adjustment - At a minimum, chair arms should be height adjustable. Optimally the arms are also width adjustable and/or offer a pivot so you can place the arm pads where they support you best while typing.	
Quality Casters - Often overlooked, but this is important, as your entire body weight is supported by one or two casters when entering and exiting your chair. Cheaper casters break often.	
Stable Wheel Base - Minimum five-spoke caster base.	
Lumbar Support - The lumbar support needs to be adjustable to place in the correct position. Sometimes this is accomplished by changing the chair back height. Ideally the lumbar is independently height adjustable. On some chairs, the depth and/or pressure of the lumbar support is also adjustable.	
Encourages Posture Changes - You'll be more comfortable over a long work day if you change positions occasionally. Movement helps increase blood flow and alertness and prevents deep vein thrombosis. This can be as simple as getting up and taking 5 minute mini-breaks during the day, but rocking or changing your back angle every so often can also help.	

Table 2: Attributes of an Ergonomic Chair, adapted from ISO-5970:1979

(a) **Back Static Load Test**: Apply the test load of appropriate magnitude perpendicular to the back under load. Maintain the load for at least 10 seconds, and conduct the test of the application at least 10 times. For chairs with spring rocking action, gradually increase the tension so that the least possible rocking movement is obtained.

(b) **Seat Static Load Test**: Position the load 100mm back from the front edge of the seat and apply the appropriate downward force 10 times, each for 10 seconds. The highest load before failure shall produce a greater rating.

(c) **Seat Fatigue Test**: Apply 950N of force to the loading pad, located at the center of the seat. Apply the force repeatedly, but not exceeding 40 cycles per minute. The

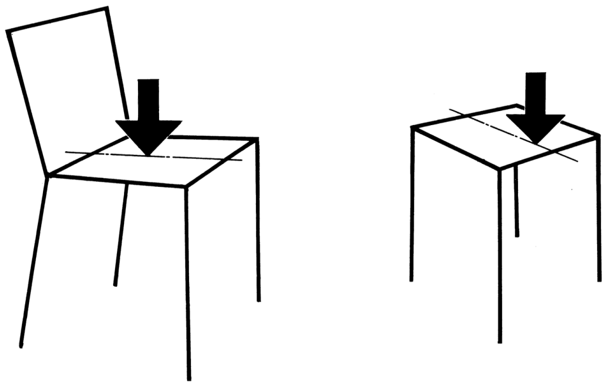


Figure 1: Seat Load Diagram [ISO:7173]

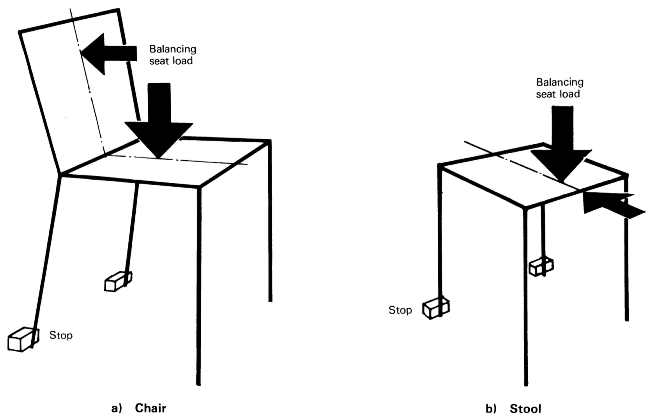


Figure 2: Back Load Diagram [ISO:7173]

difference of the lowest position of the pad during the first and last cycle shall determine the deflection of the seat.

(d) **Back Fatigue Test**: Position the loading pad 100mm bellow the top of the back. Place stops behind the rear feet or castors to prevent moving, and conduct the test by repeatedly applying 330N of force. Do not exceed 40 cycles per minute, and apply a force of 950N for each cycle.

Constraints on Chair Parameters

1. **Commuting**: Commuters, forming a relatively large percentage of Engineering Science students, make use of MY150. Any chair design should not exclude commuters from using

them.

2. **Dimensions**: Size must meet sizemark 6 of ISO-5970:1979 (chosen to best accommodate the average height of Canadians in 2005, which was 176 cm according to [6]). The sizemarks can be found in Table 1.

3. **Weight**: The total weight must not exceed twenty kilograms. This was adapted from the average weight of chairs in [11].

4. **Ergonomics**: The chair should not violate the minimum or maximum dimensions for chairs outlined in [8].

5. **Cost**: Recommendation must cost less than or equal to the current chair price ($500).

6. **Teamwork**: Must have lateral clearance of at least longer than ECF computer lab tethers (3-5 feet). The ECF computer lab chairs often inhibit effective communication by limiting the range that the swivel chairs can reach.

7. **Strength and Durability**: The back static load for testing must be at least 410N, according to ISO standards [12].

Chair Rating Criteria

1. **Theft Prevention**: 'Yes' means a higher rating than a 'No'.

2. **Dimensions**: All sizemarks except for sizemark 6 defined in [8] are unacceptable.

3. **Weight**: Lower total weight results in a higher rating.

4. **Ergonomics**: Higher number of attributes results in a higher rating.

5. **Cost**: A lower cost results in a higher rating.

6. **Teamwork**: Collaboration and interaction diminish as a function of distance [7]. A higher lateral clearance allows more collaboration and interaction, therefore a higher lateral clearance is consistent with a better rating.

7. **Durability and Useability**: The higher number of tests enumerated in the metric that the chair could theoretically withstand, the better the rating.

Existing Chair Solutions

1. **Tethered ECF chairs**: The chairs in the ECF lab [5] utilize a cable to connect the chairs to the table in order to prevent theft. Although these chairs allow for some free movement and meet many attributes defined in Table 2, the tether attached does not allow for users to easily and safely rotate their body orientation as the cable can interfere with the movement of the legs. The limited lateral clearance as a result of such a tether also hinders collaboration.

2. **Myhal Lecture Hall Chairs**: There are two types of chairs in the Myhal auditorium. There are free moving chairs and fixed chairs [2,3]. The free moving chairs do not satisfy the requirements such that they are prone to theft. The fixed Myhal chairs are similar to the tethered ECF chairs, since these chairs prevent theft such that they are fixed to the desks, and hence cannot be stolen. However, these chairs do not follow the ISO standards in ergonomics [9]. Furthermore, they do not use casters as specified in the standard, which prevents the user from moving short distances and facilitating desired interactions [7]. They also do not allow for safe rotation and movement about the desks.

3. **Myhal TEAL Room Chairs**: The Myhal TEAL Room chairs [4] contain many ergonomic attributes defined in Table 2. They also allow for great collaboration as users have almost unhindered movement. However, they lack security features making them very susceptible to misplacement and larceny. They also lack arm support, which are essential for support in the muscular system of the neck and shoulders, as well as aid for standing up and sitting down [7].

Conclusion

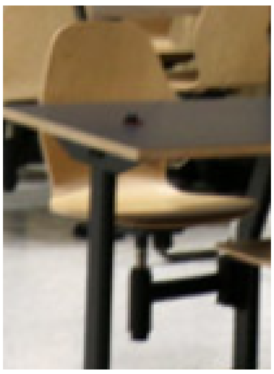
Although there are various alternatives to the chair design problem presented in this design brief, none of them adequately meets all the constraints set forth. The ECF chairs feature anti-theft requirements but limit collaboration; the MY150 chairs are ergonomically inferior; and the MY430 lab style chairs are easy to remove from their room. Thus, this design brief presents a legitimate problem that can only be resolved through design of a new chair collaboration system or through the fusion of several existing anti-theft, collaboration, and ergonomic designs.

References

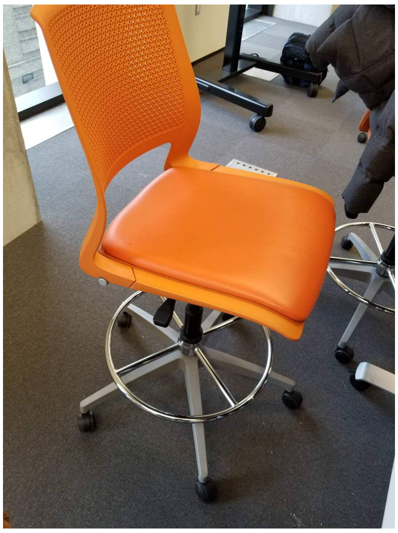
[1] Myhal Centre for Engineering Innovation Entrepreneurship. (2018). Myhal Centre for Engineering Innovation Entrepreneurship - home - Myhal Centre for Engineering Innovation & Entrepreneurship. [online] Available at: https://ceie.engineering.utoronto.ca/ [Accessed 27 Oct. 2018].

[2] Swivel Chairs in Myhal 150.

[3] Fixed Arm Chairs in Myhal 150.



[4] Chairs in Myhal 430.



[5] Chairs in the Engineering Computer Facility.

[6] Shields, M., Gorber, S. and Tremblay, M. (2018). Methodological issues in anthropometry: Self-reported versus measured height and weight - ARCHIVED. [online] Www150.statcan.gc.ca. Available at: https://www150.statcan.gc.ca/n1/pub/11-522-x/2008000/article/11002-eng.pdf [Accessed 27 Oct. 2018].

[7] http://news.mit.edu/2017/proximity-boosts-collaboration-mit-campus-0710

[8] ISO-5970-1979

[9] ISO Standard 9241: Ergonomic requirements for office work with visual display terminals (VDTs). 01-Oct-1998.

5.5.5 Arm support

For special working tasks and for moments when work is interrupted, armrests can support the muscular system of neck and shoulders and can be an aid to standing up and sitting down. For armrests with height and width adjustability, the range should cover the range from 5th percentile female to 95th percentile male of the intended user population. Where armrests are provided they:

a) should not restrict the VDT user's preferred working posture; if armrests obstruct the user they should be adjustable or detachable;

b) should not restrict ease of access to the workplace; in particular the height should not prevent the work chair being slid under the worksurface.

5.5.3.4 Castors

Castors are generally recommended for work chairs used at VDT workstations to enable users to easily and safely move for short distances within the workstation to facilitate desired proximity to equipment that supports changing task requirements.

The type of castor shall suit the properties of the floor surface. The work chair shall not travel unintentionally when occupied or unoccupied. The work chair shall not move away easily when unoccupied. Castors with a low resistance cannot be used safely on a hard floor surface.

5.5.3.5 Swivel

The swivel should enable users to easily and safely rotate their body orientation without rotating the spine or twisting the torso in order to facilitate desired proximity to equipment that supports changing task requirements.

[10] Ergonomic Chair : OSH Answers, Canadian Centre for Occupational Health and Safety, 05-Mar-2014. [Online]. Available: https://www.ccohs.ca/oshanswers/ergonomics/office/chair.html. [Accessed: 27-Oct-2018].

[11] Set of average weights for furniture, appliances and other items. Furniture Reuse Network. Available: http://democracy.york.gov.uk/documents/s2116/Annex%20C%20REcycling%20Report%20frnweig [Accessed: 27-Oct-2018].

Furniture	Chair, high / childs / rocking	11
Furniture	Chair, not padded, dining / kitchen / carver	6

[12] Mission, Facilities Services. [Online]. Available: http://www.fs.utoronto.ca/mission/. [Accessed: 27-Oct-2018]

Mission

The F&S Team is at your service!

To facilitate the academic mission of excellence in research and teaching by providing:

- A safe, clean, comfortable, sustainable and attractive environment for the University community
- Stewardship of the University's physical assets.

[13] Teamwork and Team Performance . John Wiley and Sons, Inc., Hoboken, New Jersey. Available: http://www.wiley.com/college/schermerhorn/0470294418/ppt_student/ch08.ppt. [Accessed: 27-Oct-2018].

[14] ISO Standard 7173: Furniture – Chairs and stools – Determination of strength and durability. 01-Jul-1989.