A Control Banding Approach for Safety in Shops and Makerspaces

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Invited

INTRODUCTION

Renewed interest in "making things" has led to a proliferation of small shops and makerspaces throughout educational institutions and public settings. In addition to traditional hand and machine tools, new technologies such as 3D printers, laser cutters, and small benchtop Computer Numerical Control (CNC) mills now make fabrication, rapid prototyping, and small-scale manufacturing more accessible and affordable than ever. As important as increased exposure to "making" is, bringing individuals with highly varied experience levels to such a diversity of tools can pose significant challenges to the safety and management of these facilities.

This paper describes a technique known as "control banding" for identifying, evaluating, and controlling hazards. Adopting such an approach can improve safety and increase consistency in makerspaces by providing the individuals who use them - and those who are responsible for them - with a common language and framework. The technique is sufficiently flexible to enable organizations to tailor controls and requirements to their specific needs and risk tolerance. While this guidance is provided from the higher education makerspace perspective, the concept of control banding is also applicable to K-12, community, and commercial makerspaces.

HISTORY

Control banding (as used in the health and safety field) largely evolved from work practices and engineering controls developed for handling highly hazardous materials. One of the earliest applications of control banding was by the US Centers for Disease Control and Prevention (CDC) for infectious organisms [1]. Under their system, the CDC established four risk groups of infectious agents, along with corresponding biological safety levels (BSL 1-4). Each BSL outlines progressively more stringent biocontainment measures to safely work with infectious organisms in research and clinical laboratories. The BSL concept not only defines the scope of work that can be conducted in designated BSL labs but also addresses many others aspects of working safely with biological agents.

Control banding has also been widely adopted by the pharmaceutical industry to address the protection of workers who manufacture, compound, or otherwise handle drugs with high biological activity or toxicity [2]. In the 1980s, the (United Kingdom) Health and Safety Executive applied control banding techniques to even wider workplaces [3]. Since then, the US Occupational Safety and Health Administration has also incorporated control banding into several exposure standards, including their lead and revised crystalline silica standards for construction. Several US educational institutions have also adopted control banding for chemicals used in certain research and teaching laboratories, creating "chemical safety levels" akin to BSLs [4].

Regardless of setting, control banding is designed to reduce or eliminate the time-consuming and often confusing process of performing case-by-case risk assessments for equipment, facilities, training, and procedures. The control banding concept provides a systematic approach to controlling hazards associated with groupings of materials or operations, by categorizing them and their applicable control methods into a manageable number of levels or bands.

Tools and equipment are a universal and defining feature of makerspaces. With the variety of traditional machine tools and fabrication equipment, coupled with an expanding array of new tools and equipment, the concept of control banding provides a mechanism for ensuring safety in makerspaces. This process relies upon a review of tool and machine hazards, classification into levels or bands based upon those potential hazards, and a range of additional characteristics driven by the classification. However, in addition to the specifics of control banding, it is essential to also address the role of culture, and specifically instilling a culture for safety within makerspaces.

TOOL AND MACHINE HAZARDS

The first step to applying control banding to a makerspace is to review and evaluate the intrinsic hazards within these spaces. Machines, tools, and equipment can pose a range of potential hazards to users, others nearby, and property. Some hazards have been long recognized, other hazards are less obvious, and for some new equipment, the inherent hazards are not yet fully understood.

The most obvious hazards posed by tools and equipment are acute physical injuries at the point of operation, i.e., where the tool and workpiece meet. These injuries may include lacerations, pinching or crushing, amputation, and even death. The cause of the injuries may include entanglement and unintended contact with the machine or tool, as well as flying objects from the workpiece or the tool itself.

Less obvious hazards are posed by inadvertent contact with moving components and with elements of the tool power transmission system(s). Heavy tooling or the workpiece itself can break or fall, resulting in crushed and broken fingers, hands, feet, and toes. Handling a workpiece immediately after processing may result in cuts from sharp edges or burns from friction-generated heat. Open flame use and many metal cutting/grinding operations can generate hot particles and sparks, creating hazards of burns and fire. Cutting, by both torch and laser, and welding operations also create intense infrared, UV, and other light hazards which can cause eye damage.

Often under-appreciated are the potential chronic health impacts that some tools can pose, such as hearing impairment (due to high levels of noise) and soft tissue injuries (resulting from repetitive motions and heavy lifting). Many machine actions also generate hazardous dusts, fumes, gases, or vapors. Certain workpiece materials themselves can produce hazardous emissions, such as vapors and dust from pressure-treated lumber, disturbances to lead-based paint surfaces, machining reactive metals, and thermal cutting PVC, acrylic plastics, and other materials. Preliminary studies on some emerging technologies such as 3D printing have also raised questions about chemical emissions and the creation of ultrafine particles [5].

In addition to the hazards to operators and nearby personnel, the concept of safety can also be extended to prevent damage to the tools and equipment. It is also important to review the hazards of the products that are designed and fabricated within makerspaces.

Equipment and tool hazards can be controlled through a combination of user training, machine safeguarding, and the adoption of a culture for safety within the working space. These three components are essential to the application of control banding within makerspaces.

MACHINE SAFEGUARDING AND SAFETY DEVICES

Machine safeguarding refers to purposeful steps taken to reduce or eliminate the hazards associated with a tool, machine, or other piece of equipment. These may be inherent in the design of a tool, installed during manufacturing, or added by the owner after purchase. Guards, covers, and enclosures are among the most common safeguards used to limit bodily access to hazardous machine actions. Additional safeguarding features include power controls, interlocks, as well as thermal, load, and power limitations/protections. Emergency stops, although secondary to safeguarding, provide a means to stop a machine in reaction to an incident or hazardous event. In essence, safeguarding features become a component of the tool.

Practices for tool and machine safeguarding have been developed by manufacturers, professional societies (such as the American National Standards Institute [6], National Fire Protection Association [7] and National Safety Council [8]) and government agencies (Occupational Safety and Health Administration (OSHA) [9]).

OSHA machine guarding standards technically only apply to employers and employees, but it is common practice (and strongly recommended) that they be applied as minimum requirements for tools used by anyone. While OSHA's standards provide specific guarding requirements for a limited number of distinct tool types, their General Machine Requirements are applicable to almost all tools. The American National Standards Institute provides detailed guidance on the tool safeguarding process, and the National Safety Council offers specific recommendations on machine guarding and control. It is also recommended that makerspace tooling and equipment meet or exceed these applicable guidance criteria. In addition to publications and on-line materials, these organizations also sponsor machine and tool safety training courses and provide other resources.

While there is a substantial amount of information available on machine and tool operations and safeguarding, the coverage is not necessarily comprehensive for every piece of equipment. User manuals generally provide detailed safety information for new equipment sold in many parts of the world. But with robust international and used equipment marketplaces, safety features and the associated safety information can often be incomplete or missing.

A review of machine tool and equipment hazards is an appropriate backdrop for presenting the concept of safety control banding within makerspaces. The tool and equipment classification methods in safety codes and standards form the framework for a comprehensive hazard classification system that establishes collections, levels, or bands of equipment with similar characteristics of potential harm.

HAZARD CLASSIFICATION

Control banding is proposed as a system to classify machine tools and equipment within higher education makerspaces. The classifications are based on the hazards associated with each specific tool to the user and nearby personnel. Factoring into the classification for a specific tool or piece of equipment are the power of the device, the presence of safeguards (that cannot be bypassed), and possibly the operating modes of the tool or piece of equipment (and the reliance of those operating modes on enclosures and interlocks).

The concept of safety control banding is not only a classification mechanism for tools and equipment, but also serves as the driver for establishing features of the makerspace room environment, user training, access, and oversight. The classification categories are presented in this section, followed by a discussion of these other features.

Risk (defined as the product of the probability of an accident and the severity of the resulting injury) is actually a preferred metric for a classification system. For example, while severe injuries are rare, minor lacerations and punctures from razor knives, chisels, and screwdrivers generally account for a disproportionate number of accidents in makerspaces, due to their frequent but often incorrect use. Unfortunately, reliable statistics are not available for quantifying risks from the more than 40 different families of common makerspace tools. Furthermore, OSHA's machine guarding requirements are prescriptive, making the potential hazards the more appropriate metric using the severity of potential injury as the delineating factor between each safety control band classification level.

The presented safety control band model is suggested as a template for institutions to create their own guidelines. While the presented model uses four tiers of control bands, programs can expand or contract this number to best meet their needs. To operationalize the concept of safety control bands within an academic makerspace, each band must be associated with policies that guide user training, access, use, and oversight appropriate to each hazard level.

Based upon a methodology developed at Yale University on student use of machine tools and equipment, the safety control band classification system presented in Table 1 uses four levels to categorize machine tools and equipment (and their subsequent use) [10] .

The provided examples are generalizations for machine tools and equipment. In practice, a hazard review is required for each tool to ensure that each is properly classified. For example, most Fused Deposition Modeling 3D printers might be classified as "Hazard Class 1" while Stereolithography 3D printers warrant a higher classification level based on the composition of the photosensitive liquid resin used in a specific printer. Similarly, 3D printers capable of printing metals or requiring corrosive washing should also be classified at a higher level.

Appearing in multiple hazard classification categories, CNC versions of manually-controlled machines must be carefully evaluated since different manufacturers provide different features, many of which are embedded in the system's operating software. When classifying such equipment, it is critical to verify the presence and function of all guards, enclosures, interlocks, and emergency stops.

APPLICATIONS OF CONTROL BANDING

The concept of safety control bands is proposed within makerspaces as a guide for the training, access, oversight and use of machine tools and equipment. A summary of the safety control band approach within makerspaces that details how this classification extends beyond the tools and equipment is presented in Table 2.

The concept of safety control bands can also be extended to define the classification category for specific areas within the makerspace, with appropriate levels of access control then used to ensure that only qualified individuals can use specific equipment at prescribed times. Specifically, the hazard classification of tools into categories in turn determines the classification for those areas that house this equipment in the makerspace. This methodology also leads to the development of requirements for the room's safety infrastructure, user training, supervision and oversight, and accessibility.

Table 1. Hazard-based Safety Control Bands

	Hazard Class 1
Hazards:	Minor injuries, addressable with basic first aid kit or ice
Power:	Less than 0.25 HP, 2-4 Amp, 120 VAC or less than 18V DC
Type:	Low power hand and small bench tools
Examples:	Manual hand tools, small cordless drills, glue guns, palm sanders, soldering tools, heat guns, sewing machines, 3D printers, 3D scanner, vinyl cutter
	Hazard Class 2
Hazards:	As above, plus more significant first aid injuries, potentially requiring medical assistance
Power:	0.25 to less than 0.5 HP, less than 10 Amp, 120 VAC or 18 to less than 24 V DC, and specialized enclosed/interlocked CNC tools
Type:	Low to medium power tools
Examples:	Mid-range powered hand tools, laser cutters, pneumatic tools, small benchtop tools, self-standing manual tools (shear, brake, roller, press), low powered CNC mills, routers and lathes (interlocked/enclosed), thermal foam cutters, thermal formers
	Hazard Class 3
Hazards:	As above, plus potential for serious lacerations and minor amputations that require medical attention
Power:	Greater than 0.5 HP, greater than 10 Amp, 120 VAC or greater than 24 V DC
Type:	Powerful portable and light industrial tools
Examples:	Portable construction-scale power tools, medium power industrial tools (generally free-standing), 3D printers/processes with toxic chemicals/corrosive wash steps, CNC interlocked/enclosed equipment (mill, lathe, plasma cutter, waterjet)
	Hazard Class 4
Hazards:	As above plus potential for serious amputations and life-threatening injuries
Power:	As above, plus typically self-standing and hardwired (including higher voltages and/or 3-phase power)
Type:	Large industrial tools
Examples:	Powder-actuated tools, industrial-scale mills and lathes, table saws, large (open format) robots, powered shears, rollers, brakes & presses

Under this approach, the highest hazard tool(s) present within a specific room determines the overall classification of the space itself. However, if that tool(s) can be effectively locked out or otherwise rendered inaccessible or inoperable, the overall room classification can be "downgraded" to the next lower tool hazard class.

Table 2. Control banding approach for tools and machines

Tool "Hazard" Classes	Low → high (potential hazards, complexity, cost)
Examples	Manual → high power / industrial (lists of specific tools)
Access	Open 24/7 → restricted access space/tools
Supervision & Oversight	Solo work → buddy → formal supervision
User Training	Self-taught → extended training
Credentialing	By training → demonstrated competency
Supervisors	Student peers → professionals & faculty

Room Safety Infrastructure
All spaces must be designed and built to meet basic life and fire code requirements. Similar to laboratories, makerspaces must also provide additional features to control their potential hazards. While most of these features apply to virtually all shops and makerspaces, some are likely only necessary for spaces with higher hazard equipment, materials, or operations. Basic room infrastructure features for most makerspaces include:

- High degree of "visual porosity" into the space,
- Slip-resistant flooring,
- Adequate general and task lighting,
- Sufficient general ventilation,
- Posted rules and safety information,
- Multi-purpose dry powder ABC fire extinguisher,
- Landline phone with emergency contact numbers listed,
- First aid kit,
- Prominent personal protective equipment station, and
- Access to operating manuals and instructional materials.

Depending upon the tools, materials, and operations present, additional features may be necessary, including:

- Replacing dry chemical fire extinguishers with CO_2 or other "clean" agent devices where laser cutters, 3D printers, and other electronic or optical equipment could be damaged by powder,
- Additional ventilation and filtration for fumes and/or dust,
- Wider array of personal protective equipment,
- Room or individual tool access control(s) in the form of punch codes or identification card readers,
- One or more room-level emergency shut-offs,
- Tool out-of-service (lock-out/tag-out) station,
- Emergency eyewash where exposures to chemicals may occur (and deluge emergency shower if corrosive compounds are handled),
- Flammable storage cabinets,
- Hazardous chemical waste collection and signage,
- Binder or file for material safety data sheets for chemicals and chemical products.

User Training
The users of makerspaces often have diverse backgrounds. Some may have extensive and even professional machining or carpentry experience. Others may have very little familiarity with basic hand tools. Consequently, training requirements for those accessing a makerspace and using the tools within must be carefully thought out to ensure appropriate training is consistently performed. The intensity of tool-specific training should vary depending on the Hazard Class of the specific tool. These levels of training may include self-guided instruction, peer-based instruction, and hands-on training methods by professional staff. As with all safety training, documentation of each person's participation in each training session is essential. In addition to the initial training, a robust safety program will also include a qualification process (to demonstrate safety awareness and proficiency), as well as a certification process (to identify the tools each user is certified to use). The following examples illustrate a spectrum of training methodologies that span all of the presented hazard classification levels.

Minimum training requirements must be established for everyone accessing a makerspace, including those who do not intend to use tools. Typical training at this level includes emergency response procedures, familiarization of the space layout, identification of the approved activities, an understanding of activities that require additional approval, and an awareness of what tools may not be used without additional training. Specific training should be provided to address the Hazard Class 1 tools and equipment that are generally available within the space. This training may be performed in an orientation session and should be documented with a signed acknowledgement of the makerspace policies.

Training for Hazard Class 2 tools could include demonstrations by qualified peers, staff or supervisors, as well as self-education using equipment manuals, on-line training aids, and instructional videos. A qualification instrument needs to be administered to ensure the training was effective, with this qualification determined before a user is certified to operate the Hazard Class 2 tools and equipment.

It is expected that training for Hazard Class 3 tools and equipment would require hands-on work, with the training and oversight provided by a competent person as designated by the institution. Machine tool and equipment training within this hazard class would thoroughly address tool-specific hazards and safe operating procedures. The qualification process would demonstrate proficiency with the tools and equipment, as well as knowledge of the hazards associated with each piece of equipment or machine tool.

Training users to operate Hazard Class 4 machine tools and equipment would normally be conducted over a period of time, most likely in a series of sessions. Typical training for machines in this hazard class level would include instruction as well as hands-on experience with each user completing a specified project. The project may be used as a component of the qualification process. For many institutions, this training is delivered and the process is overseen by qualified shop managers, designated staff, faculty members, and post-docs.

Supervision and Oversight

Each higher education makerspace should be affiliated with a specific organizational entity, department, or school within an institution, and have a designated individual responsible for all operations within the space. That individual should have full authority over the space and its use. This individual should have experience with all of the tools in the space, and be accountable to the institution through the affiliated organizational structure. Wider oversight of the space can be accomplished through a steering committee or other administrative body.

At the day-to-day operational level, tool and equipment access would be a function of the specific safety control band practices and the supervision required within each hazard category. Using this approach, these parameters determine which tools and equipment are available for use at any time, depending on the prescribed levels of supervision for each tool (as well as pre-determined schedules of equipment and space use). For example, makerspaces providing access to the lowest hazard tools may permit solo use of specified equipment and tools, but require a peer escort and peer oversight for using Hazard Class 2 tools. Due to increased power and the associated increased potential for harm, however, the use of Hazard Class 3 and 4 tools would be restricted to periods when supervision by professional employees or faculty would be available.

Accessibility

The effectiveness of well-defined training and oversight requirements for makerspace users is highly dependent on the ability to restrict access to authorized users. The use of identification card access to limit access to authorized makerspace users is widely used as a control mechanism. Identification card access (and monitoring) systems afford institutions the ability to grant or deny access, limit operating hours and maintain a record of users accessing a space. Additional controls can be considered to limit access to higher hazard tools within a makerspace. Such systems have also been incorporated on specific pieces of equipment (such as 3D printers and laser cutters) to control access and record use.

Zones within a makerspace may also be used to provide a second tier of access controls to higher hazard tools (which by the classification system require higher degrees of supervision). For example, Hazard Class 3 and 4 equipment tools can be located inside a room within a makerspace. Card access to the inner room can be restricted to those authorized to oversee the use of the Hazard Class 3 and 4 tools and equipment in that space. Alternatively, equipment and machine tools with a higher Hazard Classification can be locked out to restrict access within the same space where lower Hazard Class tools and equipment are located. Lockable tool power disconnects and operational switches, along with the proper levels of controlling key access, are required for spaces exercising this option.

An additional method to limit access to higher hazard equipment is to power that equipment on a controllable electrical panel. Such a panel would only be activated using a keyed switch or card reader. Access to the power would only be provided to designated individuals (who are authorized to oversee work on that equipment). With this method, a makerspace containing equipment with a high Hazard Class can effectively be de-rated to permit users to utilize the space for activities using lower Hazard Class tools and equipment when the prescribed oversight is not available.

A CULTURE OF SAFETY IN MAKERSPACES

The concepts of community and culture are key to makerspaces. The term makerspace not only refers to a physical location and its equipment but also includes the people and programs that use and define the space. The community aspect of a makerspace is a factor that differentiates these spaces from other work sites, with the typical makerspace community being a collaborative and cooperative environment to learn, share and create in. These activities define the culture of the makerspace, and typically the culture is a permissive one (regarding freedom of work) as well as collaborative (regarding the exchange of ideas). In general, makerspace cultures are nurturing and accepting of makers at all levels of experience and interests.

Adopting a positive culture of safety is essential for safe operations within makerspaces. Key to this awareness is the recognition that safety is as important as every other aspect of making. A culture for safety establishes safe operating processes as the normally- expected behavior. It adopts a mindset within the community that safe operating practices are a collective responsibility, with members watching out for one another with respect to the safe operation of tools, equipment, and constructed devices.

The many challenges faced by makerspaces help justify viewing safety as an essential component of the community's culture (as opposed to the view that safety is a prescribed set of policies, with punitive actions resulting from noncompliance). These challenges include fluid membership and use, with new users continuously joining the community and the types of projects underway always changing. A culture of safety recognizes that not every condition can be predicted and prescribed, but is sufficiently flexible to embed safe operations in every activity. A culture of safety understands that created objects can have inherent hazards, and safe operating principles must be applied when using these objects.

Key to a culture for safety is the perspective that safety is practice-based and not enforcement-driven. With such a perspective, equipment is operated in a safe manner because it is the proper way of doing things as opposed to the view that safety is something that is done because of prescribed rules. Training, qualification, and certification by designated instructors is another attribute of an organization with a culture for safety, as are the concepts of space-bands and time-bands where access is provided to trained users at specific periods of time.

Essential to the culture for safety is the establishment of community-based practices that enforce personal accountability. In such communities, dialog about safety is commonplace as a means to establish norms, promote best practices, and improve systems. Where appropriate, lessons learned from accidents (and near-accidents) should be shared within the community to help prevent future mishaps. The cleanliness and order of the makerspace is another important aspect that often correlates with safety. Finally, with respect to higher education makerspaces, it is suggested that a safety review be part of every student project.

The measures of success within a makerspace include the observance of safe operating practices as well as the regular (self-motivated) use of personal protective equipment. A makerspace in the process of developing a culture of safety will likely see an initial increase in the accident and issue reporting as the community expands its dialog on this topic. As users learn and practice rules and norms, the community will begin to help each other with these and other activities. Frequent and engaged interactions between users and managers/instructors also mark a strong culture of safety. Risk is reduced by the collective actions of all to increase environmental and safety awareness, reduce hazards and exposures, and implement realistic control and operating processes.

CONCLUSIONS

The concept of safety control bands is presented as an operational framework within higher education makerspaces. This concept is based upon the classification of hazards associated with specific machine tools and pieces of equipment. The makerspace can be designed to group similarly classified tools and equipment in specific locations, with access to and use of these spaces managed by the makerspace's staff. Thus, the concept of safety control bands extends to the space's infrastructure, as well as the training, access, oversight, and ultimate use of each machine tool and piece of equipment. Four levels of hazard have been identified to classify tools and equipment, with examples of the levels of training and oversight needed for using the equipment. These guidelines are offered as a template for defining a system of safety control bands as one component to improve the culture of safety in higher education makerspaces.

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