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A framework for using data and collaboration to drive prevention through engineering design: Reducing injury and severity in greenhouse and nursery workers ☆

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ABSTRACT

Introduction: A framework of collaboration between safety professionals and design engineers was proposed that provided direction for utilizing analysis of quantitative and qualitative data to prevent worker injury. This interdisciplinary, context-steeped approach can be utilized across a variety of industries to promote risk reduction by designing equipment and processes to prevent common workplace injuries in the first place. Safety professional expertise in regional worker's compensation claims analysis (including statistical analysis on a quantitative basis and qualitative analysis of trends in written injury descriptions of circumstance) provided the starting point for identifying industries of interest for this approach. *Method:* Followed by education of design engineers on safety approaches (including hazard identification, the ANSI/ASSP Z590.3 consensus-based standard), tools such as risk assessment matrices and methods for effective on-site work observation and interviews with workers affords transfer of knowledge. Design engineers then utilize safety influenced design problem identification and goal criteria to create and select concepts for eventual detail design and prototype testing on-site. This approach was implemented in a case-study at a Midwest greenhouse industry facility site in summer of 2019. Two problem areas were identified and addressed with two unique engineering designs that were prototyped and utilized at the facility with success. *Practical Application:* This approach can apply to other industries and collaborative teams in the future to prevent worker injury by design.

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1. Introduction

Safety professionals are on the front lines of addressing the impacts of the occupational environment, equipment, and processes regarding worker health and safety, but safety professionals rarely have the opportunity to design-out problems early in the lifecycle or to engineer solutions proactively. Reactive measures such as worker training or personal protective equipment are often deployed, instead of using preferred risk-reduction strategies in the hierarchy of controls. Conversely, design engineers are involved in the design of facilities, equipment, tools, and processes, but may lack knowledge of prevention-through-design (PtD) principles to apply to their work. Engineers rarely observe the long-term effects designs have on worker populations and their health and safety. Without this knowledge, they are unable to incorporate modifications into new, improved designs that are safer for workers. Workplaces would benefit from the disciplines working together to use engineering design for safety.

Agriculture continually ranks as one of the highest hazard industries for fatal and nonfatal injuries. The reliance on education-based injury prevention for agricultural workers has not been shown to have statistical significant reduction in injury rates per a review of over 100 research studies (Rautiainen et al., 2008). As in other agricultural sectors, large immigrant and non-English native language populations can make translation of safety and health practices or educational efforts challenging. These considerations make the need for engineering controls especially important, to eliminate the hazard or reduce the risk without dependence on worker knowledge, English proficiency, experience, or decision-making. Engineering and design interventions have

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been successful in other agricultural sectors (Chapman et al., 2004; Meyers et al., 2002).

Nursery and greenhouse industries are important, multi-billion dollar sectors of national agricultural production, with nursery and horticulture sales alone totaling 13.8 billion in 2014 (USDA, 2014). Operations require a high rate of production in a relatively small land area (Lea-Cox et al., 2010), with an average acreage (72 acres) about one-fifth the size of average U.S. farm operations (418 acres) (USDA, 2009). Operations and establishments tend to differ from other sectors of agricultural crop production in a number of ways. Greenhouse, nursery, and floriculture operations have higher than average farm operation sales, lower government payments, and greater likelihood of internet access on-site. Farm operators tend to be younger and more likely female or minority (USDA, 2009). Combined, greenhouse, nursery, and floriculture operations represent only 2.5 % of farms nationally, yet pay 13.3% of farm labor expenses and employ 4.9% of farm workers (USDA, 2009). Horticulture producers reported a 16% increase in production expenses from 2009 to 2014, topping $11 billion. Hired labor accounted for the largest percentage (37) of production costs and increased 13% from 2009 (USDA, 2014).

Notably, multiple employers and hired labor is common in these agricultural establishments, which often triggers OSHA, workers' compensation, and other safety and health and insurance

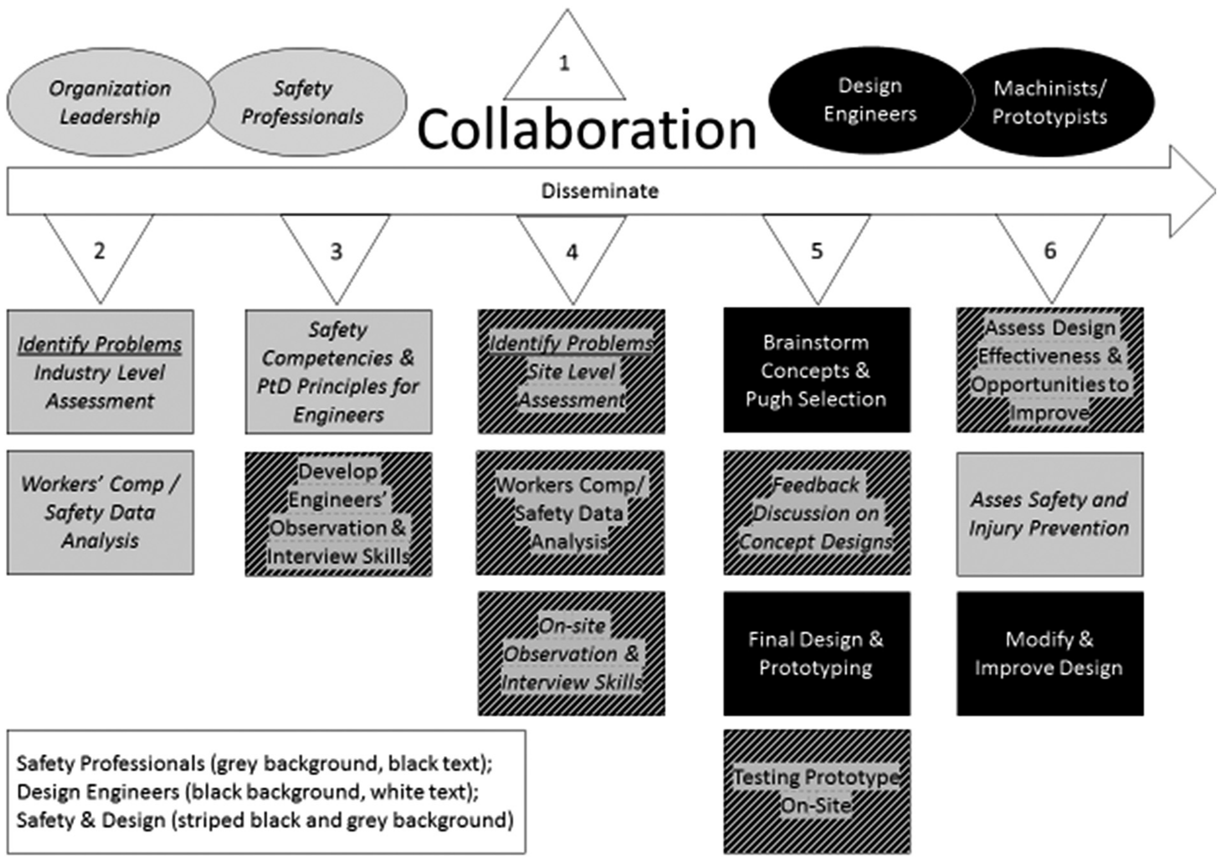

Fig. 1. Framework for Using Data and Collaboration to Drive Prevention through Engineering Design. 1) Safety professional identifies task, tool, or workplace in need of safety engineering design intervention. Note: many workplaces are high-risk, small, underserved and/or under-resourced and may lack an internal safety professional. An external safety professional, industry partner (e.g., insurance loss prevention) or local professional organizations (e.g., trade groups, unions, American Society of Safety Professionals (ASSP)) can assist in identifying prospective workplaces. Safety professionals, organizational leadership and identified engineering team prepare for collaborative project. Engineering team may be internal, or external partners such as an academic institution. 2) Identify potential injury risks, loss sources, or safety issues. Analyze injury, workers' compensation, and task data for the industry, workplace, or occupation to determine leading causes of injury, risk factors, and other areas of safety concern or priority. If internal data is not available, the Bureau of Labor Statistics (BLS) data is publicly available and can be used to ascertain major injury and loss sources for industries and sub sectors of interest based on North American Industry Classification System (NAICS) codes. 3) Introduce engineering students/professionals to prevention-through-design principles and build occupational safety competencies. The ANSI/ASSP Z590.3 consensus standard "Prevention Through Design Guidelines for Addressing Occupational Hazards and Risks in Design and Redesign Processes" provides a foundation for engineers involved in a collaborative project. Safety professionals can provide further background on hazards, risk assessment, and decision-making related to the work premises, tools, equipment, machinery, substances, and work processes. Develop the engineers' skills in on-site observation and worker interviews through human subjects' research training and development of guides to help gather information at the participating organizations. Safety professionals and organizational leadership can establish goal-setting for the engineering design concepts developed. 4) Gather information during an on-site assessment to identify problem areas. Site-specific safety data, workers' compensation, OSHA, or other injury data should be requested and reviewed by the engineering team. Mixed methods (injury rate data analysis, observation, and worker interviews) help to uncover problem areas that are feasible to be improved through engineering design. Prioritize problem areas by developing weighted criteria relevant to the organization, workers, and potential engineering design and prototyping process. Select the highest priority problem areas to address, and then create status quo risk assessment matrices (RAMs) for each problem area. 5) After the problem areas are identified, the engineering design process is employed. Prioritize potential interventions by injury frequency and severity reduction potential, cost, implementation feasibility, timeframe, and overall impact (Schneider, 1998). Starting with brainstorming concepts, design engineers utilize Pugh matrices to select concepts for further design, gain and incorporate feedback on concepts from safety professionals' organizational leadership, then create final designs and estimate changes to RAMs for designs before prototyping these designs for testing within the organization on-site. Open communication between design engineers and organizational leadership allows for timely feedback and on-site expertise to inform the engineering design process. Implement the design on-site. 6) Post-implementation of the safety engineering solution, create a plan to assess and evaluate the design and user experience. Collect data and compare pre-and post-implementation risk or injury reduction. Make changes if necessary, redesign, and continuously improve.

requirements. This, arguably, provides greater opportunity for safety and health practices, injury prevention, and injury record-keeping and data collection for these workers.

Though hazards may be similar to other agricultural sectors, the nursery and greenhouse sector have areas of highly mechanized (potting/canning/lines) operations, on-site shipping and loading, high square footage of buildings and structures, and a high percentage of indoor working environments (Meyers et al., 1997), plus highly concentrated (acreage) operations. Previous literature has highlighted risks and ergonomic priorities for tasks in this sector (Meyers et al., 1997; Schneider, 1998), creating a focused foundation of knowledge to combine with data from this project. Additionally, in comparison to other agricultural sectors, nursery and greenhouse workers have a higher paid (USDA, 2009) and more stable workforce, thus injury reporting and management may be more complete.

Workers' compensation (WC) data are a unique source of information on injuries and associated costs experienced by workers' and orgnization. Employers purchase WC insurance and claims are triggered in the event of a workplace injury or illness. Rules of coverage and claim benefits are dictated by individual state statue. WC data may include injury characteristics, worker demographics, a text-description of injury event details, medical and lost wage costs, and sometimes payroll or other denominator data. WC can allow for identification of injury incidence, rates, risk factors, and trends over time. Aggregated data from many establishments and across different insurance policyholders can be especially valuable to identify trends or risk factor for injuries across industries or occupations, and for events that occur infrequently or those that small employers have never experienced but are still at risk for. The ability to identify injury rates, risk, and trends, plus knowledge of existing priorities in the field, can establish a basis for engineering interventions.

The object of this research was to ascertain injury characteristics in an established nursery and greenhouse worker data population using workers' compensation injury claims and evaluate injury and severity based on worker, job, and injury event characteristics; determine areas of high injury prevention priority and engineering design feasibility; innovate and test efficacy of an engineering intervention to prevent a high priority nursery industry injury using a contextual design approach; and develop a framework for safety professionals and engineers to use data and design principles to reduce the burden of injury in an occupational setting. This research project provided the unique opportunity for both safety professionals and design engineers to see new perspectives and collaborate to prevent injury by design.

2. Methods

2.1. Development of conceptual collaborative framework

This project developed and used a conceptual framework (Fig. 1) for data analysis and interdisciplinary collaboration to drive injury prevention through engineering design, with the goal to improve workplace safety. The framework (Fig. 1) focused on safety/organizational leadership and engineering/design and their roles in the process. Six conceptual steps of the collaboration pro-

Table 1
Example Problem Areas Identified and Weighted Criteria Comparison.

Criteria	Weight	Pot Hole Driller	Plant Transport	Ladder Fall Protection
Likelihood of Use	5	2	1	1
Worker Time Reduction	4	2	1	0
Injury Frequency Reduction	5	1	1	0
Injury Severity Reduction	5	1	0	1
Cost to Build	2	0	0	2
Ease of Implementation	1	2	2	2
Timeframe to Completion	5	1	1	2
Total Time in Use	3	0	2	2
# People Impacted	2	0	2	0
Design Challenge	4	1	1	−2
# of Touches Reduction	4	1	0	0
Company Safety Priorities	2	2	0	1
Worker Safety Priorities	4	0	2	1
Total Weighted Score	**-**	**47**	**43**	**30**

Risk Assessment Matrix		Severity			
		Catastrophic	Critical	Marginal	Negligible
Probability	Frequent	High	High	Serious	Medium
	Probable	High	High	Serious	Medium
	Occasional	Serious	Serious	Medium	Low
	Remote	Medium	Medium	Medium	Low
	Improbable	Low	Low	Low	Low

Fig. 2. Reference Baseline Risk Assessment Matrix Severity and Probability Index.

Table 2
Workers' compensation claim characteristics in nursery and greenhouse workers.

Gender	N	%
F	329	29.9%
M	772	70.1%
Age		
Under 21	59	5.4%
21–25	174	15.8%
26–30	163	14.8%
31–40	236	21.4%
41–50	215	19.5%
51–60	202	18.3%
61 and over	47	4.3%
Unknown	5	0.5%
Severity		
Lost time > 3 days lost work	135	12.3%
Medical only	966	87.7%
Cost ($) (total incurred valued 3/2019)		
<1000	788	71.6%
1-–10 K	226	20.5%
10-–25 k	33	3.0%
25-–100 k	39	3.5%
>100 K	15	1.4%
Injury Nature		
All Other	49	4.5%
All Other Cumulative Inj.	1	0.1%
All Other Occupational Disease	3	0.3%
Amputation	2	0.2%
Burn	7	0.6%
Carpal Tunnel Syndrome	3	0.3%
Concussion	4	0.4%
Contusion	194	17.6%
Crushing	2	0.2%
Dermatitis	7	0.6%
Dislocation	3	0.3%
Dust (Pneumoconiosis)	1	0.1%
Foreign Body	63	5.7%
Fracture	18	1.6%
Heat Prostration	4	0.4%
Hernia	2	0.2%
Infection	9	0.8%
Inflammation	35	3.2%
Laceration	130	11.8%
Multiple Physical Injury	13	1.2%
Myocardial Infarction	1	0.1%
No Physical Injury	6	0.5%
Poison/Chemicals	1	0.1%
Puncture	54	4.9%
Rupture	1	0.1%
Severance	1	0.1%
Sprain	39	3.5%
Strain	443	40.2%
Syncope	4	0.4%
Vision Loss	1	0.1%
Body Part		
Back	163	14.8%
Head and Neck	181	16.4%
Lower Extremities	216	19.6%
Multiple Body Parts	77	7.0%
Trunk/internal/Body Systems	71	6.4%
Upper Extremities	387	35.1%
Unknown	6	0.5%
Injury Cause		
Absorption/Ingest/Inhalation/Irritate	34	3.1%
Animal or Insect	41	3.7%
Caught In, Under, Between	28	2.5%
Caught, Puncture, Scrape	29	2.6%
Chemicals	12	1.1%
Dust, Gases, Fumes Or Vapors	3	0.3%
Fall Ice/Snow	30	2.7%
Fall/Slip Same Level	92	8.4%
Fall/Slip, Different Level	40	3.6%
Falling/Flying/Misc. Struck By	56	5.1%
Foreign Body In Eye	64	5.8%
Hold/Carry	27	2.5%
Lift/Handle	213	19.3%
Motor Vehicle	18	1.6%
Object	32	2.9%
Other	37	3.4%
Pull/Push/Reach/Twist/Strain	171	15.5%
Repetitive	45	4.1%
Stepping On Sharp Object	9	0.8%
Strike/Step On	14	1.3%
Temp Extremes/Exposures	8	0.7%
Tools/Equipment/Machinery	98	8.9%
Grand Total	**1,101**	**100.0%**

cess to prevent injury by design and improve workplace safety were outlined.

2.2. Implementation of the framework

The collaborative framework (Fig. 1) was adapted for use within an academic institution and implemented through an undergraduate mechanical and industrial engineering design capstone course. Safety and injury prevention curriculum was added to the requirements of the engineering capstone course so an engineering project focused on safety and injury prevention could be completed for an industrial host site. The University engineering team was led by faculty with safety and design engineering expertise, and also included four senior undergraduate engineers, a graduate student, and a machinist. The faculty recruited a local greenhouse industry partner for a host site. The host site contributed their organizational leadership and their internal safety professional for the project. The host site and University team collaborated following the conceptual steps of the framework (Fig. 1).

2.3. Analysis of Worker's compensation and injury data

A workers' compensation (WC) dataset (2000–2017) from a regional insurance provider to the greenhouse sector was used. The dataset included claims from Illinois, Iowa, Minnesota, South Dakota, and Wisconsin. Insurance class codes broadly classify groups of businesses by operations and risk. The following insurance class codes were selected to encompass greenhouse and nursery employers and workplaces: 0005, Nursery Employees and Drivers and 0035, Farm- Florists and Drivers. Injury claims were coded by the insurance providers according to the Workers' Compensation Insurance Organizations (WCIO) codes for part of body, nature of injury, and cause of injury. Additional data included worker job, gender, age, text description of the injury event, and dollars paid and incurred (paid plus reserved). Claim severity was classified as medical-only or lost-time (<3 calendar days away from work) and by claims cost metrics.

A combination of injury characteristics and text descriptions were used to categorize injuries into groups according to root cause(s) and/or intervention opportunities, with an understanding that circumstances surrounding injury events may be multifactorial and not mutually exclusive. Descriptive tables were used for injuries illustrating frequency, severity, and percent of total.

2.4. Employee interactions and on-site activities

The University team met with organization leadership, toured the facility, and conducted on-site observations and employee interviews over multiple days in the summer of 2019. The team observed workers performing tasks or in situations that had resulted in injury or were known to be high-risk, which was informed by the injury data, industry trends, and host-site feedback. Observations occurred during operational hours and encompassed multiple shifts. Hazards, challenges, and potential solutions were noted during observation during site visits by students. Additional observations were made after intervention selection to assist with the design process. Twenty-one employees were interviewed while working (in English and in Spanish with help of a contracted interpreter) to determine worker concerns and injury risk factors. Before going on-site, approval of a research protocol for human subjects was successfully sought from the University of Minnesota Institutional Review Board (# STUDY00006306) and only the approved interview guides (Appendix A) were utilized when asking questions. Design, implementation, and adoption of interventions aimed to take into account cultural and native language characteristics of affected workers. Native language translators and interpreters assisted in the investigations and research to help assure accurate stakeholder feedback and injury prevention design and adoption use for risk reduction (Anders et al., 2006; Liebman et al., 2014; Luque et al., 2007; Messias et al., 2013).

2.5. Engineering design and prototyping process

A systematic approach to engineering design was followed; starting with problem identification, concept design, concept selection, to detailed or final design (Pahl & Beitz, 1996). A co-design approach was utilized where feedback from end users (workers), safety professionals, organizational leadership, and machinists (prototype manufacturers) was all sought at relevant parts of the engineering design process to influence the design outcomes (Durugbo, 2014).

Student engineers used the analysis of workers' compensation and injury data for a foundational understanding of injury risk in the greenhouse industry and insights into circumstances surrounding worker injuries. The University team met with organizational leadership for an overview of safety programs and concerns specific to their greenhouse and nursery operations. The University team conducted on-site observation and employee interviews (detailed in previous section). Hazards and risks were identified from observation of worker activities and tasks using equipment and through speaking with workers during interviews. The research team completed the qualitative and quantitative analysis of interview data and identified potential problem areas to address.

Feedback from safety professionals and organizational leadership was a starting point for the group to establish injury prevention problem areas and criteria weightings (Table 1). These potential problem areas were evaluated using a method called Pugh Concept Selection. In Pugh Concept Selection a matrix of criteria is created to rate the importance of each different concept for each criterion (Pugh, 1991). The two problem areas with the highest overall ratings across all criteria were selected for concept development.

Baseline risk assessment matrix scores were evaluated for both selected problem areas using the definitions for severity and probability shown in Fig. 2. The greenhouse company and organization did not express awareness or a plan to deal with the risks associated with the equipment and activities involved in the problem areas, though they did have risk control measures in place for other hazards (e.g., pesticides). Risk assessment matrices (RAMs) were utilized as a simple tool to visualize the changes the new proposed engineering designs could make to injury frequency and severity as compared to status quo operations. RAMs are commonly used tools in a variety of industries by safety-concerned professionals (Bao et al., 2017). Different problems associated with consistency of application and thus results in RAMs have been identified (Anthony (Tony) Cox, 2008; Duijm, 2015). This research project addressed these issues by utilizing quantitative scales when comparing all problem areas for probability of occurrence and severity of injury, which were detailed in a previous publication about this project (Klesmith et al., 2020).

Per a co-design design process, stakeholder feedback was essential throughout the entire design process. The University team made multiple site visits to conduct further observations and make measurements in the problem areas. From these observations and the data analysis, the engineering design team generated three design concepts for each problem area, which were then sketched. The team developed criteria to evaluate concept performance, compared the three concepts for each problem area across these criteria using Pugh Concept Selection, and presented the findings and research to the industry partners. The concepts were evaluated by safety professionals and leadership within the organization during a separate in-person meeting, relying heavily on partner feedback, ultimately determined two projects to take to the final design and prototyping stage of the process. Before prototyping, a formal design critique and review of the prototype designs was under-

(a) (b)

Fig. 3. Problem areas identified included (a) unguarded equipment used for pot hole drilling and (b) narrow walkways for plant transport.

taken by a team of experts, including machinists, with relevant professional experience. After including feedback from the industrial partners and expert evaluators, the University team built and installed the prototypes with the support of the industrial partner for a trial period.

3. Results

3.1. Worker's compensation injury characteristics

Results showed that 49 establishments in the nursey and greenhouse sector incurred a combined 1101 injuries with an overall injury rate of 4.9 per $1 million of payroll, 12.3% of which resulted in lost-time. The majority (71.6%) of all claims had an incurred cost less than $1000, with another 20.5% under $10,000. The relatively low-percentage of lost-time claims, and large proportion of low cost claims indicates fairly low overall claim severity in the population.

Young workers (age 25 and under), combined, suffered 21.2% of all injuries. Regarding gender differences in injury rates, 70.1% of injuries were to males, but notably 29.9% of injuries were to females, potentially reflecting an underlying population with a greater percentage of females than other agricultural sectors. The most frequent injuries nature included sprains (40.2%), contusions (17.6%), and lacerations (11.8%). Upper extremities accounted for 35.1% of injuries. Hold/carry (2.5%), Lift/handle (19.4%), and Pull/Push/Reach/Twist/Strain (15.5%), and Repetitive (4.1%) combined, caused the largest percentage of injuries (41.5%). Tool, equipment,

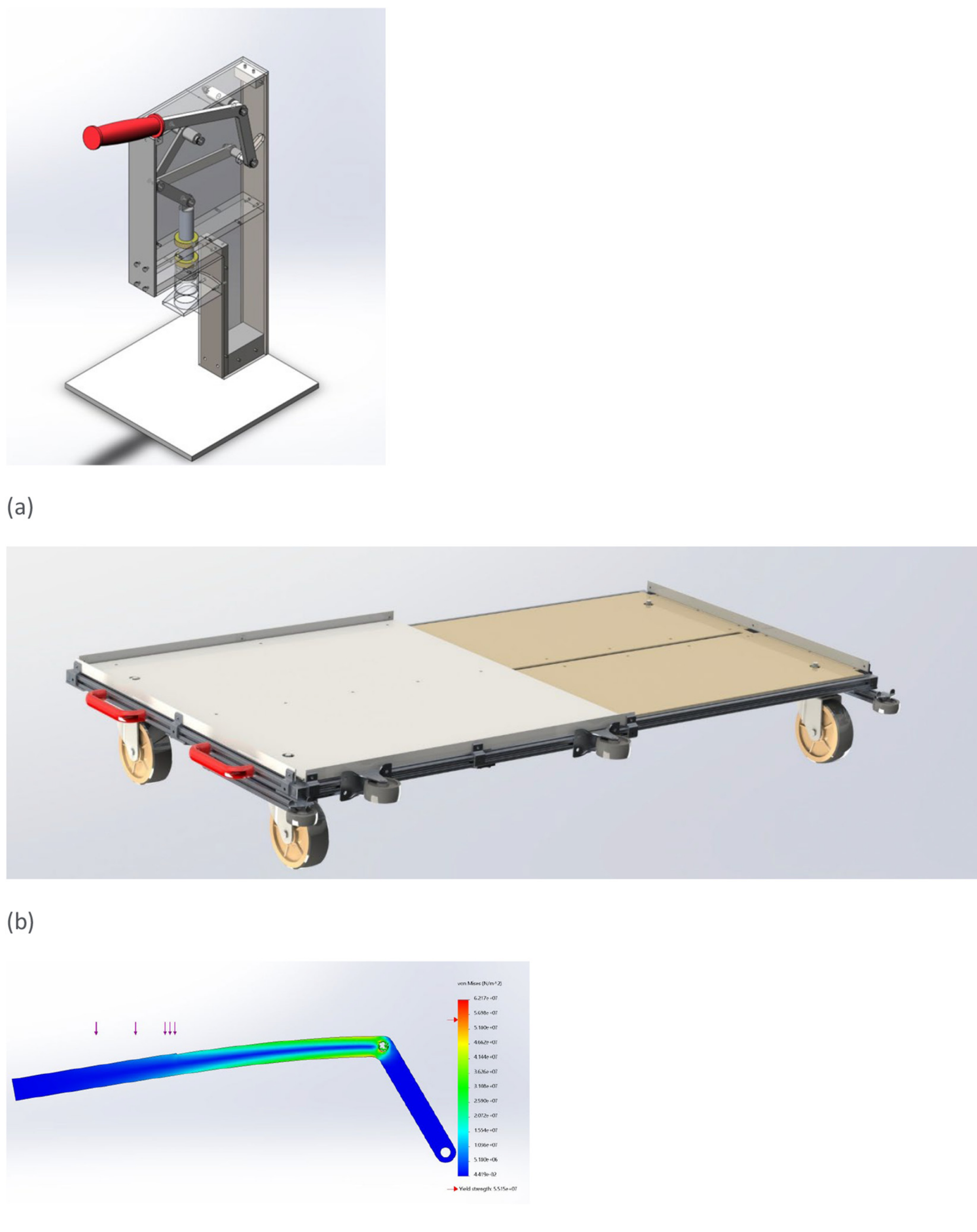

Fig. 4. CAD assembly for (a) pot-hole punch. (b) plant cart, and (c) FEA of pot hole punch handle.

and machinery-related causes resulted in 8.9% of total injuries (Table 2).

Further review of the frequencies combined with text description of injury events revealed that high-severity injuries involved: moving/loading trees, erecting/maintaining greenhouses, and material handling. Frequent injuries involved: hand tools, material-handling, hand-digging, lifting/moving equipment, and operation of motorized vehicles. The WC results provided some initial insights for the engineers of potential high-priority areas for injury prevention.

3.2. Problem area scores

The team developed the following criteria (Table 1) based on Pugh Concept Selection (Pugh, 1991) to combine safety, organization, worker, and engineering design concerns. Each criterion was weighted on a scale from 5 (most important) to 1 (least important), which demonstrated priorities to addressing problem areas. For example, the criteria likelihood of use; injury frequency; and injury severity reduction, were all rated **5** as the most important criteria for selecting a problem area to address. The team rated every problem area on each criterion on a scale of 2 (excellent) to −2 (terrible) in steps of one for five different rating levels the same as the weights themselves. A total weighted score was calculated for each problem area by multiplying the problem area criteria ratings by the criteria weights. In total, eight different problem areas were considered, rated, scored, and compared. The *pot-hole-driller* and *plant transport* problem area (Fig. 3) weighted total scores were both greater than the *ladder fall protection* problem area, even though not every criterion was weighted higher for the former two problem areas as compared to the latter one (Table 1). The *pot-hole-driller* and *plant transport* problem areas were rated the highest and selected for engineering design. (Table 1). The goals of redesign of the problem areas were reduced worker risks of repetitive hole drilling with unsafe equipment for hanging basket pots and reduced repetitive lifting and carrying tasks on greenhouse tables and over uneven surfaces and narrow walking paths during plant inventory movement (Fig. 3).

(a) (b)

Fig. 5. Prototype designs for (a) pot hole punch and (b) greenhouse plant transport at UMD.

(a)

Probability		Severity: Catastrophic	Critical	Marginal	Negligible
	Frequent	High	High	Serious	Medium
	Probable	High	High	Serious	Medium
	Occasional	Serious	Serious	Medium	Low
	Remote	Medium	Medium	Medium	Low
	Improbable	Low	Low	Low	Low

(b)

Probability		Severity: Catastrophic	Critical	Marginal	Negligible
	Frequent	High	High	Serious	Medium
	Probable	High	High	Serious	Medium
	Occasional	Serious	Serious	Medium	Low
	Remote	Medium	Medium	Medium	Low
	Improbable	Low	Low	Low	Low

Fig. 6. Pot Hole Drilling Problem Area RAMs (a) pre and (b) post intervention evaluation area shown in white.

(a)

Probability		Severity			
		Catastrophic	Critical	Marginal	Negligible
	Frequent	High	High	Serious	Medium
	Probable	High	High	Serious	Medium
	Occasional	Serious	Serious	Medium	Low
	Remote	Medium	Medium	Medium	Low
	Improbable	Low	Low	Low	Low

(b)

Probability		Severity			
		Catastrophic	Critical	Marginal	Negligible
	Frequent	High	High	Serious	Medium
	Probable	High	High	Serious	Medium
	Occasional	Serious	Serious	Medium	Low
	Remote	Medium	Medium	Medium	Low
	Improbable	Low	Low	Low	Low

Fig. 7. Plant Transport Cart Problem Area RAMs (a) pre and (b) post intervention evaluation area shown in white.

3.3. Prototyping

The team made detailed designs of the developed solutions, specific to the problem areas, using CAD (computer aided design) software SolidWorks (Fig. 4a, 4b). The team performed finite element analysis (FEA) on the computer modeled assembly to assess material durability and feasibility of use (Fig. 4c).

A **plant pot-hole-punch** (Fig. 5a) and a **greenhouse plant transport cart** (Fig. 5b) were prototyped and tested to reduce risk from the *pot-hole-driller* and *plant transport* problem areas.

3.4. Pre and post safety engineering design comparison

The old and new designs were compared in a pre and post-intervention risk assessment matrix (Fig. 6) (Fig. 7) – this helped quantify the potential for risk reduction that injury prevention by design created. *Pot-hole-drilling* changed from serious and medium severity and probability (Fig. 6a) to low with the new **pot-hole-punch** design (Fig. 6b). The cart changed from serious and medium severity and probability (Fig. 7a) to serious, medium and low severity and probability (Fig. 7b).

The hole-punch (Fig. 5a) eliminated electrical hazards, unguarded moving parts, and dust generation. The new, manual design improved ergonomic positioning and reduced force/grasp requirements, and reduced hole-generation from 14 seconds to ~ 2 seconds. The cart (Fig. 5b) reduced strain, fatigue, and lifting demands on staff members, and made table loading/unloading tasks easier. Additionally, the cart allowed a greater number of plants to be transported simultaneously (10/12 vs. 6/7). Together, these factors improved navigation of walkways between tables and reduced risk of strain, trips, falls and contusions and lacerations caused by collision with tables.

The cost to produce the **pot-hole-punch** prototype totaled $500. Additionally, the punch required no electricity use as compared to the *pot-hole-drilling* machine, further resulting in cost savings for any greenhouse. This machine cost is affordable to most greenhouse organization who drill holes in pots currently. Furthermore, there was only one *pot-hole-driller* in use at the organization. The previously used *plant transport task* went from medium severity and probability to medium–low with the new plant **transport cart** prototype. The total cost to prototype both a 5′x3′ and a 3′x3′ greenhouse **plant transportation cart** totaled $1500. The old carts used at the greenhouse organization were custom-made in-house of unknown price. There were many of the custom made carts in use at the organization in many areas. All prototype designs would likely cost less with design for manufacturing changes that would be undertaken if production increased in scale. For the **pot-hole-punch**, the benefits to injury rate prevention and utilities cost reduction would easily justify use of the new prototype as compared to the existing method.

4. Discussion

The implementation of the framework through an academic engineering design course was successful for this project. Student engineers gained valuable exposure to safety engineering principles and practice and were able to complete a capstone project that fulfilled both engineering requirements and reduced employee injury risk in a workplace. The project will serve as a model for continued integration of safety engineering into the design capstone course.

The design solutions were implemented into practice, but post-intervention data collection was not feasible due to Covid-19 restrictions. Informal communications with organization employees indicated that the **pot-hole punch** (Fig. 5a) and the plant **transport carts** (Fig. 5b) are used in greenhouse. To fully complete the collaborative engineering design process, the team should obtain feedback and assess design effectiveness and opportunities for possible improvements from the client organization. The designs should be in use through multiple work periods, shifts, seasons, and or handled by different workers. For future collaborations and efforts, this step (and subsequent data) will be an important focus. In some cases, it may even be possible to gather injury rate data from the organization again and compare pre and post project implementation.

The timeline of this project was exceptionally limited by the academic summer session, which was only 12 weeks in length (versus 16 weeks during the regular academic year). Student completed all classroom-based engineering curriculum, added safety curriculum, initial workers' compensation data analysis, site visits, design, material ordering, prototyping, and final worksite presentation in this time period. Given more time and resources, the engineering team could have created designs that were larger in scale or for additional problem areas beyond the top two rated problem areas. Yet, the results were evidence of the impactful things that could be accomplished in even a very brief time frame, which provides proof-of-concept that this can be replicated in future design courses and/or for safety engineering problems that need rapid mobilization and resolution.

5. Conclusions

The research provided a greater understanding of risk factors in greenhouse and nursery workers. We were able to pilot an interdisciplinary approach to rapidly deploy and implement engineered intervention to reduce injury risk. The process of problem identification, to design and prototyping, in collaboration between safety professionals and engineers, is feasible for implementation within many different workplaces. The conceptual framework allows for adaptation, especially if the workplace does not have internal safety and/or engineering design professionals. This methodology could be widely used and would be especially impactful in agricultural, high-risk, under-served, and/or small business establishments. Additionally, site-specific engineering solutions/ prototypes may have a wider industry translation to other agricultural or applicable operations.

The authors are particularly interested in further refinement and implementation of the framework into engineering program curriculum and design courses in academic institutions and using the design course safety engineering projects as a way to positively impact organizations and workers. This pilot project data will be used to apply for a larger scale test of a contextual design engineering approach to reducing nursery and greenhouse worker injury rates, and in other high-risk workplaces. The next step is to translate this trial beyond a minimal number of partners to many industrial sites, partners, and industries through multiple iterations of design that are analyzed for evidence based improvement of worker injury rates.

5.1. Practical applications

This framework for collaboration between safety professionals and design engineers has the potential to be applied to industries outside of nursery greenhouse production. Many work environments and manual tasks offer numerous opportunities to design out injury. Interdisciplinary collaboration can effectively identify hazards and risks in a way that is feasible to create new tools and processes and reduce injury burden, especially in high-risk, small, underserved, and/or establishments with minority employee populations**.** Establishment of a collaborative partnership with an academic institution within the framework can further provide benefits of training and educating future engineers.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Worker Interview Guide
Group: Physical laborer, greenhouse worker
Goals for the Interview:

- Discuss any personal injuries that have happened on the job site and what circumstances lead to the injury, who was involved, what equipment was involved, what time of day, day of the week, and season.
- Discuss any injuries that have happened to other people and what has led to those.
- Discuss the environment of the nursery and what are standard procedures and whether those procedures are followed or not, when and why.
- Discuss any safety concerns.
- Discuss any safety protocols.
- Discuss any formal or informal rules followed by workers that influence health & safety.
- Discuss opinions about using personal protective equipment or working with more than person while loading.

Key Questions:

- Have you been injured on the job site and if so, would you mind explaining the injury and what lead up to the injury?
- Have you seen or heard of anyone else that has gotten hurt on the job site and could you explain what the injury was and what lead to it.
- Are there any safety concerns that you currently have right now in your current job?
- Are there any safety protocols in place to keep you safe?

Appendix B

Participant Observation
Key Notes:

- Always act in a kind and professional manner when observing or interacting with participants.
- Respect the participants' wishes. If they don't want to talk to you don't push it. Simply say "Thank you for your time and if you would like to participate in the study let me know".
- Make it clear up front what your purpose is. Say "We are trying to gather information to make the workplace safer." This will help people trust you if they understand your intent.
- Observe from a distance so you don't get in the way of the workers.
- Ask questions to the workers if you have them. You can only gain so much knowledge from watching.
- Try to build a rapport with the participants. Build trust. Start off with shorter observations to build rapport.
- Dress in an unobtrusive manner.
- Become familiar with the settings before observing people.
- Make sure to stay out of walkways, away from needed equipment, and in a safe location. Move as needed to accommodate work and workers.
- Try to explain things in a simple way, where it is not too technical or detailed.
- Pay attention. From what is going on around you, to someone's body language, every detail could be important.
- Try to recreate the situation on paper by using either words, drawings, or both.
- If someone is speaking Spanish and might need a Spanish interpreter, go get the interpreter and come back.
- Try to separate what you know about the problem from what the participants are telling you.
- Write notes as you are observing to help you remember later, the act of writing by hand helps encode memory in your brain.
- After observation and as soon as you are able write down by hand or type up your thoughts, observations, memories, detailed drawings of the situation, layout, and worker movements that you saw that day.

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