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Work-Based Curriculum to Broaden Learners' Participation in Science: Insights for Designers

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Abstract Around the globe, science education during compulsory schooling is envisioned for all learners regardless of their educational and career aspirations, including learners bound to the workforce upon secondary school completion. Yet, a major barrier in attaining this vision is low learner participation in secondary school science. Because curricula play a major role in shaping enacted learning, this study investigated how designers developed a high school physics curriculum with positive learning outcomes in learners with varied inclinations. Qualitative analysis of documents and semistructured interviews with the designers focused on the curriculum in different stages—from designers' ideas about learning goals to their vision for enactment to the printed materials—and on the design processes that brought them to fruition. This revealed designers' emphases on fostering workplace connections via learning goals and activities, and printed supports. The curriculum supported workplace-inspired, hands-on design-and-build projects, developed to address deeply a limited set of standards aligned learning goals. The curriculum also supported learners' interactions with relevant workplace professionals. To create these features, the designers reviewed other curricula to develop vision and printed supports, tested activities internally to assess content coverage, surveyed states in the USA receiving federal school-to-work grants and reviewed occupational information to choose unit topics and career contexts, and visited actual workplaces to learn about authentic praxis. Based on the worked example, this paper offers guidelines for designing work-based science curriculum products and processes that can serve the work of other designers, as well as recommendations for research serving designers and policymakers.

Keywords Curriculum · Design · Work-based learning

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International trends in educational reforms for compulsory schooling envisage that all learners participate in science education, irrespective of their academic and vocational interests (NRC 2015; Osborne and Dillon 2008; Tytler 2007). This vision applies to a broad range of learners, from those aspiring to pursue advanced education and careers in STEM fields to those seeking to join the workforce after completing compulsory education. In bringing this vision to fruition, educators face a sizable roadblock with low numbers of learners pursuing science courses during secondary schooling, a serious problem noted in many countries. For example, 64% of secondary school graduates in the USA did not complete even one course credit in physics, and 30% did not complete it in chemistry in 2009 (Kena et al. 2016). Similarly, only 14% of year 12 learners in Australia studied physics, 18% studied chemistry, and 24% studied biology in 2012 (Kennedy et al. 2014; Marginson et al. 2013). In the UK and elsewhere in Europe, countries are also experiencing challenges with attracting learners to science and technology education (Sjøberg and Schreiner 2005; Smith 2011). Thus, an important challenge faced by schools and curriculum developers internationally is finding ways to serve learners with varied career inclinations, and reaching out especially to those who are presently disinclined to engage with science.

To that end, a key issue to address is learners' perceptions of the lack of relevance of science and technology curricula. International recommendations advocate elucidating how learning science can give learners access to various careers that are attractive to them (Osborne and Dillon 2008), sometimes by promoting interactions between learners and STEM professionals (Marginson et al. 2013). Further, experts stress the development of instructional approaches that promote applications of scientific concepts in real-world contexts, and cultivate reasoning and problem-solving (Tytler 2007), for example, by embedding engineering design activities in school curricula (Marginson et al. 2013). Engineering practices and design problems are seen as a means to deepen learners' understandings of scientific ideas, to make science learning meaningful, and to highlight the value of science in everyday lives and society (NRC 2012, 2013). To enact this vision, teachers are advised to include performance tasks, open-ended questions and discussions that encourage exploration of ideas, instead of eliciting only right answers (NRC 2015).

Problem Statement

Work-based science curricula at the secondary school level can help address the urgent need for developing critical thinking and problem-solving competencies in all learners, but these are challenging to create. One main difficulty lies in generating learning experiences that are authentic, appealing, and rigorous—all of which are required to promote *deep understanding* and *rich performance*. Curricula should help learners comprehend and integrate key concepts, principles, and models to make sense of phenomena in the world (Duschl et al. 2007). They need to help learners develop knowledge of the practices by which these ideas are created and utilized (Duschl et al. 2007; NRC 2012). Finally, curricula must also invite learners to demonstrate their depth of understanding through rich performances that involve reasoning and applications of scientific ideas and practices via cognitively demanding tasks (Tekkumru-Kisa et al. 2015).

To create such curricula, designers need rich exemplars describing products and processes linked to finished designs (Howard et al. 2012). Existing literature from the fields of instructional design (e.g., Gustafson and Branch 2002) and curriculum design (e.g., Thijs and van den

Akker 2009) sheds some light on key processes for creating instructional products. Further, the science education literature has described design processes to address challenges in supporting learners (Edelson et al. 1999; Kanter 2010; Krajcik et al. 2008), and to create educative curriculum materials for teachers (Davis et al. 2014). However, literature that offers fine-grained examples or design process guidelines for work-based science curricula is severely lacking. This, together with the fact that designers themselves often have limited knowledge of suitable workplace problems and practices that are of interest to the majority of learners, means that designers struggle to create work-based curricula that draw on authentic and appealing occupational contexts. Thus, there is a need for robust examples of work-based curricula, as well as insight into the processes that bring them to fruition.

Goal and Significance of the Study

The goal of the study is to produce a worked example of a powerful work-based curriculum that aimed to broaden learners' participation in science, as well as of its design processes. Akin to process-oriented worked examples in other fields (see Van Gog et al. 2004), this example aims to reveal the rationales and reasoning in designers' thinking about their product, and to demonstrate key strategies that they used to create it. Whereas generic resources exist, such as instructional design models (Gustafson and Branch 2002) or case examples for teaching instructional design (Ertmer and Quinn 2007), this study speaks to the need for rich exemplars of design products and their underlying processes, making accessible designers' decisions and reflections on the finished products (Howard 2013; Howard et al. 2012). By offering insight into the designer reasoning behind a work-based curriculum for all learners that is also aligned with international literature, this worked example can be valuable to science educators internationally.

Context of the Study

The worked example focuses on a work-based curriculum which showed evidence of positive learning outcomes for learners with different aspirations: 4-year college, 2-year college, vocational-technical education, and workforce-bound (see Methods for a full set of curriculum selection criteria). Although the designers believed their product was suitable to all learners, including college-bound learners who were eager to explore different technical careers, the curriculum was targeted especially at learners who were generally disinclined to study physics. These learners typically opted out of science courses after 2 years of secondary school; many of them were turned off by traditional abstract science pedagogy and did not find science engaging or relevant. The curriculum used an innovative approach to make physics relevant to learners' lives and potential careers beyond school. It linked standards (reforms)-based science learned in school with science applied in different work settings related to engineering and technology, and used engineering design projects in the classroom to engage learners with scientific knowledge, practices, and problems tackled by engineers and technicians. The curriculum contained a teacher guide, learner resource book, and learner activity sheets called *job sheets*. These materials covered five units, and each unit lasted about 6 weeks. When enacted as a sequence, the units covered a full year of secondary school physics. The following section describes the theoretical underpinnings for the retrospective analysis of this curriculum.

Theoretical Framework

Curriculum Manifestations

Designers' ideas for helping learners attain deep understanding and rich performance in science manifest in different forms of the curriculum. This study focuses on three curriculum manifestations that are particularly salient to the work of designers: (a) the *outcomes* designers intend to achieve, (b) their *vision* for enactment in the learning environment, and (c) the *written* materials specifying and supporting teaching and learning activities. Referred to in curriculum theory as "curriculum representations" (Goodlad et al. 1979; van den Akker 2003; Walker 1990), this notion emphasizes that curricula are reified in different ways. To produce high-quality curricula, the manifestations need to be consistent with one another (McKenney et al. 2006). This section describes the meaning and importance of these manifestations, and designers' challenges in relation to each.

Intended Outcomes The intended outcomes (IOs) are learning objectives that designers set out to achieve, namely the scientific ideas and practices they hope learners would comprehend. These are positioned in relation to the overarching vision (Thijs and van den Akker 2009), and can be articulated as performances specifying how learners should apply their understanding of scientific ideas and practices (Krajcik et al. 2008; Rivet and Krajcik 2004).

Attention to IOs allows designers to select specific phenomena that learners can study to understand the target scientific ideas and practices (Krajcik et al. 2008), and to identify alternative learner ideas that will need to be addressed in the curriculum materials (Rivet and Krajcik 2004). Designers use IOs also to plan assessments so they can measure the intended performances (Krajcik et al. 2008).

Designing IOs in science curricula for all learners involves particular challenges. For example, science standards in policy documents cover a broad range of content, but treating scientific ideas deeply requires selecting fewer standards to formulate the IOs (Krajcik et al. 2008). Further, sequencing of scientific ideas targeted in the IOs may need to deviate from the traditional disciplinary structure to make them coherent and relevant to the particular learning activities emphasized in the curriculum (Sherin et al. 2004)

Envisioned Enactment Envisioned enactment (EE) refers to instructional activities designed to help learners attain the IOs. These are tasks to engage learners with specific scientific ideas and/or practices (Tekkumru-Kisa et al. 2015). When designers envision enactment, they may plan instructional activities with particular structures (Songer 2006) and patterns to support learners in eliciting and integrating ideas (Linn et al. 2003); inquiry-based investigation projects with driving questions (Edelson et al. 1999; Linn et al. 2003; Squire et al. 2003); design projects for learners to perform (Kanter 2010; Kolodner et al. 2003; Sadler et al. 2000); teachers' role in facilitating teacher-learner discussions (Kolodner et al. 2003); and organizational matters like location and learner grouping (Thijs and van den Akker 2009). Attention to instructional activities is critical because these influence not only the disciplinary knowledge that learners comprehend but also how deeply learners engage with and apply that knowledge (Tekkumru-Kisa et al. 2015).

Designing instructional activities for learners with different career inclinations requires attending to authenticity, engagement, and connections with scientific principles. Authentic practices are typically complex and unfamiliar to novices, and it is challenging for designers to

reduce the complexity of those practices while preserving their core elements (Edelson and Reiser 2006). Further, whereas authentic practices and sustained investigation can promote learners' understandings (Edelson et al. 1999), these activities demand high learner motivation. Finally, design tasks can motivate learners but it is often difficult to maintain strong connections to underlying scientific principles while they engage in artifact construction (Kolodner et al. 2003). Specifically, designers need to ensure all target content is useful in performing the tasks, but this is challenging because learners may find the content relevant but not necessary to complete the tasks (Kanter 2010).

Written Curriculum The written curriculum (WC) embodies designers' ideas about EE and IOs (Thijs and van den Akker 2009). The WC is crucial because learners need support to perform scientific practices (Lee and Butler 2003), and the extent of written support influences their understandings of the practices (McNeill et al. 2006; Songer 2006). Designers create different types of print-based and/or digital materials to support learners. For example, to guide learners' investigations of real-world scenarios, learner materials contain prompts to help them plan experimental procedures (e.g., Kolodner et al. 2003), to determine key evidence in analyzing data (Songer 2006), to construct explanations based on evidence and scientific principles (e.g., McNeill et al. 2006), and to monitor their progress in conducting scientific inquiry (Linn et al. 2003).

The WC typically also contains guidance for teachers to promote learners' understandings of scientific concepts and practices. Materials such as printed teacher guides facilitate teachers' daily instructional practice (Davis et al. 2016). The written supports may provide teachers with procedural assistance in implementing the curriculum and supporting learners' understandings, for example, strategies or tips for orchestrating whole class discussions (Roblin et al. 2018). Curriculum materials may also contain educative elements that are designed explicitly to promote teachers' knowledge of scientific ideas and disciplinary practices (Davis and Krajcik 2005). The materials may help teachers anticipate learners' alternative ideas about scientific concepts, and indicate how teachers can use suitable language and thought experiments to respond to learners' ideas (Davis and Krajcik 2005). The materials may also indicate what scientific content to emphasize during instruction (Davis et al. 2014). Additionally, the WC may clarify the nature and importance of scientific practices (McNeill and Krajcik 2008), and why learners should engage in these (Davis et al. 2014). The materials may also delineate characteristics of high-quality scientific practices, and suggest general and specific strategies to enact these practices (Bismack et al. 2015; Davis et al. 2014). The educative elements may appear as overviews with background information or embedded as supports within specific lessons (Bismack et al. 2015; Davis et al. 2014). To generate meaningful experiences for learners, altering tasks and objectives to suit local classroom contexts is critical; hence, curricula need to support teachers in making necessary adjustments (Barab and Luehmann 2003; Squire et al. 2003).

In developing the WC, a key challenge for designers is ensuring that learners have just-in-time access to critical information for conducting sustained investigations (Edelson et al. 1999). Moreover, scientific practices such as analyzing data and constructing scientific explanations are difficult to perform without suitable hints in learner materials (McNeill et al. 2006; Songer 2006). Nevertheless, creating prompts and hints at the right level of detail is challenging because too much specificity may turn scientific inquiry into recipes for actions, whereas too little may limit learners' engagement with inquiry (Linn et al. 2003).

Attending to teacher materials is crucial for achieving impact on learner outcomes (Roblin et al. 2018). Well-designed supports can influence teachers' curricular planning and actual instructional

practices during enactment, and thereby the opportunities available to learners (see Davis et al. 2016 for review). In this regard, curriculum materials may be considered as tools which, together with teachers' own 'pedagogical design capacity' (Brown 2009; Remillard 2005) enable them to create new or revised learning opportunities. Hence, as good tools support craftsmanship, good teacher materials support teacher customization efforts. Yet, designers struggle to balance the need for support against the risk of overloading users with too much information. For example, teachers may not always be familiar with enacting scientific practices (Knight-Bardsley and McNeill 2016; Krajcik and Blumenfeld 2006; Simon et al. 2006) or engineering design approaches (Mehalik et al. 2008), and may even hold misconceptions about the nature of scientific practices (Zangori et al. 2013). As a result, designers are tasked with creating usable written supports with suitable hints and just-in-time information for learners, as well as relevant and practical guidelines on pedagogical content knowledge for teachers to facilitate learners' understandings.

Design Processes to Yield IO, EE, and WC

Each of the IO, EE, and WC manifestations of a curriculum product are generated through systematic, iterative design processes including the core phases of analysis, development, and evaluation (see for instructional design processes Branch and Merrill 2012; Gustafson and Branch 2002). This study examines designers' specific activities in these phases that are vital in generating the three aforementioned manifestations of curricula (IO, EE, WC) that can foster deep understanding and rich performance in learners with a broad range of aspirations.

Analysis Designers often begin with this phase to understand the problem and scope for improvement (Thijs and van den Akker 2009). They study the needs of target learners and teachers, and the settings where the curriculum will be used (McKenney and Reeves 2012; Edelson 2002), as well as the target tasks to determine what knowledge and skills learners should develop to perform the tasks (Smith and Ragan 1999). Salient activities are reviewing literature to understand the problem and how others have addressed similar problems (McKenney and Reeves 2012). For example, designers review subject matter in policy documents such as science standards to identify what content needs to be taught (Krajcik et al. 2008; Rivet and Krajcik 2004; Songer 2006) and examine existing curriculum materials to understand what opportunities are specified for learning, assessment, and teacher and learner participation (Davis et al. 2014). Designers also gather data to assess needs and context of target audience (Edelson 2002), through, for example, questionnaires given to school personnel (McKenney and Reeves 2012;). Based on insights in this phase, they define the problem, formulate overall goals, and generate preliminary design specifications and requirements (McKenney and Reeves 2012; Edelson 2002) to determine the IOs, envision learning activities (EE), and plan the WC.

Development In this phase, designers explore ideas for solutions, map their details, and build prototype solutions (McKenney and Reeves 2012). They take concrete steps to address the goals and contextual considerations (Edelson 2002), striving to design instruction that is effective, efficient, and pertinent to the target audience (Gustafson and Branch 2002). Salient activities include reviewing policy documents such as standards and benchmarks in national, state, or district level science frameworks (Krajcik et al. 2008; Rivet and Krajcik 2004; Songer 2006), and prior research to derive IOs and sequences of learning experiences (Songer 2006), and studying the literature to identify strategies by which teachers can support learners (Davis et al. 2014).

Designers also gather input from scientists to identify important scientific facts in content areas (Songer 2006), and to learn about authentic scientific practices (Edelson et al. 1999). They gather feedback from teachers to situate content and IOs in real world contexts (Kracik et al. 2008; Rivet and Krajcik 2004), to envision (EE) performance tasks that require application of target science content (Kanter 2010), and to generate instructions and questions for learning activities (Edelson et al. 1999). They revisit IOs to consider sequence of concepts and requisite knowledge that should be supported (Krajcik et al. 2008), and analyze performance tasks conceptually to assess the extent of target science content that learners must apply in performing the tasks (Kanter 2010). Based on the activities in this phase, designers specify measurable IOs (Gustafson and Branch 2002), select content to be learned (Smith and Ragan 1999), envision enactment of learning tasks (EE) and their sequences to help learners attain the IOs (Krajcik et al. 2008; Songer 2006), and produce the WC as per design specifications (Gustafson and Branch 2002).

Evaluation Finally, in this phase, designers test the curriculum for both formative and summative purposes—gathering data to determine required revisions, and to assess overall effectiveness of the curriculum (Branch and Merrill 2012; Gustafson and Branch 2002). Both partially designed and complete versions of the WC are evaluated (see survey of instructional design models in Gustafson and Branch 2002). Salient activities are external expert appraisal (Krajcik et al. 2008; Thijs and van den Akker 2009), pilots of early prototypes of the WC, and tryouts or field tests of more mature prototypes in classrooms (McKenney and Reeves 2012). Designers observe teachers' enactments of materials (Davis et al. 2014) and learners' engagement in instructional activities (Edelson et al. 1999), examine learners' gains on tests of learning outcomes (Clarke and Dede 2009; Rivet and Krajcik 2004), and gather feedback from interviews with teachers (Clarke and Dede 2009; Davis et al. 2014). Based on evaluation data, designers make needed changes to the curriculum manifestations (Branch and Merrill 2012; Gustafson and Branch 2002).

Research Question

As the preceding literature review shows, prior work in the fields of instructional design and curriculum design reveals critical processes that guide the creation of instructional products. Similarly, the literature on science education describes curriculum manifestations and key design processes that can support learners and teachers. But these bodies of literature do not provide detailed insights into the manifestations of a work-based science curriculum for learners with different career inclinations, nor into the processes that help designers align these manifestations. To support science curriculum designers, therefore, this study sought to identify and analyze key design decisions in the development of a high school work-based physics curriculum that yielded positive outcomes for learners with varied career aspirations. In so doing, it aimed to produce a worked example of the curriculum product and its design processes, and to derive guidelines that could serve future work. To reach this goal, the following main research question was formulated: *What characterizes the manifestations (IO, EE, WC) of a work-based science curriculum and how do design processes (analysis, development, and evaluation) contribute to designers' thinking about alignment among these manifestations*?

Methods

Case Sampling, Characteristics, and Relevance

This research comprised a qualitative interpretive case study (Merriam 1988) of one high school physics curriculum developed previously. This method was chosen because the desired outputs were a worked example detailing a finished curriculum product and its design process (Howard et al. 2012), as well as guidelines derived from this description. The study reported in this paper was conducted in the USA, and emerged out of a larger investigation that used the following criteria to examine the manifestations and design processes of powerful science curricula developed for large-scale use: (a) designed for a K-12 audience, (b) stand-alone classroom curriculum (in contrast to supplementary or out-of-school curriculum), (c) availability of key project staff and relevant documentation, (d) intention to support deep understanding and rich performance in science, and (e) evidence of positive learning outcomes for learners. Based on these criteria, six potential cases were identified. From them, the present case was selected for its insights into designing work-based science curriculum for all learners.

The case was a full-year senior secondary school curriculum for physics credit for grades 10, 11, or 12. The researchers were able to contact the designers via email and gather documentation from the designers' organization. The curriculum was designed to help learners comprehend and apply physics concepts and the engineering design process. The curriculum was field tested with learners indicating different academic and vocational aspirations. Whereas most learners aspired to join 4-year colleges, many also planned to join the workforce after high school, and some learners aspired to join 2-year colleges or vocational-technical programs. The curriculum project's reports to the funding agency stated that in field trials held in six states in the USA, learners using this curriculum performed at higher levels on science content and process skills items from the National Association of Educational Progress (NAEP) compared to the national NAEP norms for those items.

The curriculum was developed over a 5-year period at an independent, non-profit, educational research and development organization in the USA. Throughout its history, the organization has been committed to making high-quality education accessible to learners with diverse needs and interests, and to broaden learners' participation in science. As a result, many curricula developed at this organization seek to expand learners' access to fundamental science education. The curriculum was subsequently published by a commercial publisher. It has been in commercial publication since 2006, and remains available through the publisher's catalogue and other bookstores.

The curriculum responded to two reform movements originating in the 1990s in the USA: (1) the National Science Standards advocating rigorous academic content with an inquiry orientation (NRC 1996), a precursor to the current K-12 Science Framework on integrating scientific concepts and practices (NRC 2012); and (2) the school-to-career movement (Goldberger and Kazis 1996) aimed at equipping learners with basic competencies for potential careers. The curricular mission was to teach standards-aligned science content in the context of broad career areas of interest to learners. Although the curriculum was inspired by educational policies in the USA from nearly two decades ago, and was developed prior to the Next Generation Science Standards (NGSS Lead States 2013), its focus on teaching physics in the context of careers in engineering and technology renders this curriculum and its underlying design process pertinent to the current international trends in science education reform that were described earlier. These include the importance of situating learning in real-

world settings (Tytler 2007), increasing learners' awareness of a wide range of STEM related careers in society (Marginson et al. 2013), and making school science engaging and accessible to all learners (Osborne and Dillon 2008). Further, challenges in reaching learners with diverse inclinations persist, as a major hurdle in preparing learners for successful careers in the twenty-first century includes learners dropping out of school due to perceived lack of connections between school learning and the workforce (Symonds et al. 2011).

Data Sources

In accordance with recommendations to use evidence from multiple data sources in case study research (Yin 2014), this study used project documents, the commercially published curriculum materials, and transcripts of interviews conducted with the curriculum development team to investigate each manifestation and related design processes. Table 1 describes the data sources and information obtained from each source.

Participant Sampling and Characteristics

A combination of purposeful and referral sampling was used to recruit participants with different roles and stages of work on the curriculum project. The project leader of the curriculum served as an informant to guide sampling choices (Yin 2014) by providing an initial list of designers, and additional referrals were obtained from them. Six members of the curriculum team participated in the study: the project leader, two internal formative evaluators, and three curriculum writers. See Table 2 for participants' roles, stages of work, and alphanumeric codes to distinguish among participants. In the results section, participants are identified by their roles and alphanumeric codes (P1 through P6).

Procedure

The data collection involved three steps. First, to understand the curriculum goals and materials, the researchers obtained project documents and commercially published curriculum materials from the organization where the curriculum had been developed. The researchers created a project timeline to represent key design activities and outputs, and a list of relevant documents, publications, and contact information of the curriculum team. Second, the

Table 1 Data sources used to examine curriculum manifestations (CM) and design processes (DP)

Data sources	CM	DP
Project documents (grant proposal, drafts of WC, designers' memos, progress reports)	IO; EE; WC	Analysis, development, and evaluation phases
Commercially published WC (teacher guide, learner resource book, job sheets)	WC	–
Transcripts of interviews	IO; EE; WC	Development and evaluation phases

CM curriculum manifestations, *IO* intended outcomes, *EE* envisioned enactment, *WC* written curriculum, *DP* design processes

Table 2 Participant roles and timeline of their work on the curriculum design project

Participant roles	Stages of work	Alphanumeric codes
Project leader	Entire duration[a]	P1
Internal formative evaluator	Early	P6
Internal formative evaluator	Late	P3
Curriculum writer	Early	P2
Curriculum writer	Early	P5
Curriculum writer	Late	P4

[a] Served as project leader after initial leader left, but was involved throughout the early, mid, and late stages of work

researchers met the project leader, one curriculum writer, and one internal formative evaluator in a single session. The purpose of this meeting was to verify and refine the description of the curriculum goals and project timeline prepared by the researchers. During the meeting, the draft project timeline served to aid the participants' memory and guide the initial conversation about their work. Third, six prolonged interviews (Yin 2014) were carried out, one with each of the six participants. Documents describing the curriculum goals and materials, and the refined project timeline, were emailed to the participants prior to the interviews. The interviews followed a semistructured protocol comprising four main questions, three on the curriculum manifestations (IO, EE, WC) and one on design processes (analysis, development, evaluation). Additionally, a set of prompts accompanied each main question and was used to ask for more information and/or to clarify the question. Table 3 shows the main questions and sample prompts. The interviews lasted approximately 2 h per respondent, were completed in a single session or over two sessions as per the respondents' preferences, and conducted via face-to-face and/or electronic media. The project leader was interviewed last to also clarify information from other respondents. All interviews were audiotaped and transcribed, resulting in six transcripts.

Table 3 Sample of interview questions and prompts

	IO	EE	WC	DP
Questions	What kinds of deep understanding and rich performance in science were important to you and why?	In what ways did you endeavor to elicit your ideas about deep understanding and rich performance in the classroom?	How were your ideas about deep understanding and rich performance manifested in the written curriculum?	How did your design process and activities during *analysis*, *development*, and *evaluation* facilitate the creation and refinement of these manifestations in the curriculum?
Sample prompts	Which scientific concepts and practices were important?	How did you imagine learners would build understandings of scientific concepts through classroom activities?	How did your curriculum support learners' deep understandings of scientific concepts?	Analysis: How did you learn about the target audience, context, and what was important for them to learn?

IO intended outcomes, *EE* envisioned enactment, *WC* written curriculum, *DP* design processes

Data Analysis

The document analysis was conducted in two phases. In the first phase, as stated earlier, project documents and commercially published curriculum materials were examined to create descriptions of curriculum goals, materials, and timeline of design work. This analysis was performed to guide the preliminary meeting and verify the information with a subset of the curriculum team. In the second phase, the researchers analyzed project documents to "corroborate and augment" findings from the prolonged interviews (Yin 2014, p. 107) and to generate additional findings. Specifically, the documents were used to confirm participants' descriptions of curriculum manifestations and design processes, extend those descriptions with details and examples, and to extract new information about how the designers worked to support deep understanding and rich performance.

The six interview transcripts were coded deductively with a formal scheme based on the conceptual framework and research questions (Miles and Huberman 1994), capturing curriculum manifestations and design processes. A code of "none" was applied to data that were not codable. The coding scheme was revised iteratively. The first author and another researcher independently practiced coding one complete transcript at a time. The unit of coding was a single sentence. Discrepancies in coding were resolved through discussions, and final coding decisions were established through consensus. This continued until the coders achieved an acceptable level of inter-rater reliability (Cohen's Kappa was approximately 0.87[1]). Table 4 presents the codes, their descriptions, and sample quotations from the interview data.

Results

The designers contextualized reforms-aligned physics content in workplace settings related to a variety of careers in engineering and technology. Throughout their design process, they prioritized workplace connections consistently, attended to authenticity, appeal and rigor of the science content, and developed instructional supports to deepen learners' understandings of physics concepts and engineering design practices. As an advanced organizer, Table 5 summarizes the curriculum manifestations (IO, EE, WC) embodying workplace connections, as well as the design processes linked directly to each of these. Thereafter, corresponding to each row in the table, detailed findings are presented.

IO The designers wanted learners to comprehend and integrate a limited set of key physics concepts (related to kinematics, forces and motion, electricity and magnetism, and energy), and engineering design practices such as generating questions, designing and building solutions to specifications, gathering and analyzing appropriate data from investigations, and communicating ideas orally and in writing. Further, the designers wanted learners to demonstrate these understandings via rich performances where they would apply relevant physics concepts and practices to solve design projects. By connecting physics with work in engineering and technology, the designers hoped ultimately that learners would understand how scientific knowledge was integral to many careers. As curriculum writer P5 and project leader P1

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[1] The Cohen's Kappa was computed for a total of 13 codes used in the larger investigation from which this study emerged. The study focuses on four of these codes that were relevant to the designers' work on fostering deep understanding and rich performance in learners.

Table 4 Codes used in the data analysis

Codes	Code descriptions	Code examples
IO	The learning goals in science that the designers set out to achieve	"You know, rather than it being a series of sort of disconnected reading assignments, the goal was to give students and opportunity to build their understanding of concepts, and at the same time, to help students integrate those concepts"
EE	The designers' vision of learning opportunities that would help learners attain the intended outcomes	"So we imagine that kids are working together, and to understand concepts by doing things, and that the teacher is watching and guiding, but not lecturing at all, actually"
WC	The manifestation of the designers' intentions in written curriculum materials for learners and teachers	[referring to the Teacher's Guide] "So this is a question saying, you know, like we've learned something about metals, and that metals have electrons. So what if you don't have the electrons? Then what happens if you try to put current through something. So there's like a specific question saying, well what do you think's going to happen?"
DP	The activities performed in *analysis, development* and *evaluation* phases of the design process to create and refine IO, EE, and WC	"And I believe we interviewed people there and asked them about the kinds of things that they worked on, and in some cases, we could say, what kind of science is important here?"

IO intended outcomes, *EE* envisioned enactment, *WC* written curriculum, *DP* design processes

described respectively, they wanted learners to appreciate "science as something that's actually relevant to various kinds of work," and to "be able to extract from a work site visit or an activity, the scientific concepts that were relevant to their learning."

Design Process to Develop IO To situate the curriculum in career areas that would appeal to a broad range of learners, and to select a broad career cluster (career path or major) with (a) potential for teaching standards-based science, and (b) significant demand for work-based science curriculum, in the analysis phase, the designers surveyed the 26 states in the USA receiving federal School-to-Work (STW) grants, as well as subscribers to the STW Net listserv. Through this survey, they identified Industrial and Engineering Technology (IET) as a career cluster with ample scope to address rigorous science, and for which all respondents in their survey were offering courses. This cluster included the fields of engineering, maintenance and repair, and industrial technologies, and pointed designers to potential unit topics related to these fields. In addition to surveying career areas, the designers also examined a wide range of content standards from national and state science frameworks to identify rigorous content that was recommended.

The designers' activities during development and evaluation phases yielded insights into choosing content and learning goals. Early in the design process, to choose unit topics and represent suitable occupations in the curriculum, the designers conducted a job market study of over 50 occupations in the IET career cluster. They reviewed occupational information from the *Occupational Outlook Handbook* published by the Bureau of Labor Statistics (within the U.S. Department of Labor), and distilled key aspects like knowledge and qualification for entering the field, and nationwide prevalence of the occupations. The designers also matched selected occupations with the science standards, focusing on science and technology knowledge among others. This measure led them to specify that occupations included in the

Table 5 Curriculum manifestations (CM) and design processes (DP) for fostering workplace connections

CM	DP		
	Analysis	Development	Evaluation
IO Learners comprehend, integrate limited set of key physics concepts, and engineering design processes; show rich performances where they apply relevant concepts and practices to solve unit projects; understand that science is relevant to many careers	Administered survey to states receiving School-to-Work federal grants to identify unit topics embedded in career areas of possible interest to learners, with potential to address reforms-aligned science, having demand for work-based science curriculum; reviewed content standards from science frameworks	Reviewed occupational information (pre-requisite knowledge, qualification, nationwide prevalence); matched selected occupations with science standards to choose unit topics and occupations; chose narrow set of standards to treat science content deeply	External appraisal of science standards' coverage; recommended fewer standards with more depth, revisiting standards across units
EE (a) Workplace-inspired, hands-on design-and-build projects; learners build prototype devices to explore, apply concepts, practice engineering design process (b) Minimal reading load to encourage active exploration of concepts, avoid disconnected reading assignments (c) Learners visit relevant workplaces, interact with professionals to reach beyond the classroom, see science applied on the job (d) Teachers as facilitators; elicit learners' ideas, engage them with questions and discussions	Reviewed other science curricula to identify compatible pedagogical approaches in preparing grant proposal; formulated initial vision of design-and-build projects	Compared strengths and limitations of learning activities of other science and math curricula vis à vis own aims, target audience; prioritized learner experiences, teacher practices for present curriculum; refined initial vision	Classroom testing data used to determine optimal timing in curriculum for workplace visits, make workplace visits more salient
WC (a) Science situated in broad range of potentially appealing career contexts; unit projects inspired by tasks and problems of various careers in engineering, technology	No data available	Reviewed written materials of other science, mathematics curricula to generate detailed specifications for level of support, format of learner, teacher materials; noted lack of connections between activities and context in other materials; emphasized	External appraisal suggested making workplace storylines more salient, using workplace contexts not only to engage learners' interests, but also to understand underlying scientific concepts and technical practices

Table 5 (continued)

CM	DP		
	Analysis	Development	Evaluation
(b) Storylines in learner resource book present workplace-inspired unit projects, contextualize activities and content in workplace scenarios (c) Ongoing work records in job sheets, stepwise instructions, and just-in-time background information via readings in learner resource book (d) Questions and instructions in job sheets and learner resource book to guide learners' interactions with workplace professionals (e) Guidelines to teachers for using scientific language, instructional strategies, information on learners' understanding		workplace-inspired storylines and scenarios in present materials Designers visited actual work sites to identify workplace praxis to guide supports for design projects Unit project activities tested internally by curriculum's designers to ensure sufficient complexity, applications of scientific knowledge	Classroom testing data used to revise work-based unit projects, design workplace inspired problems with potential for rich connections to science Classroom testing data used to revise instructional activities to address difficult content

CM curriculum manifestations, *DP* design processes, *IO* intended outcomes, *EE* envisioned enactment, *WC* written curriculum

curriculum should address substantive scientific content, and be comprehensible, attractive, and accessible to target learners.

Furthermore, the designers got advice from the funding agency's program officer, who examined a chart of science standards covered in each unit. He recommended addressing fewer standards in more depth, and revisiting those standards throughout the full year course, instead of addressing them only once. In developing the units, therefore, the designers chose a narrow set of standards to ensure deeper treatment of the content. As project leader P1 explained, "in each framework document, or standards document, we did not address all of the standards, because it would be impossible, we thought, to have any kind of meaningful learning."

EE The designers imagined each curricular unit would center on a long-term, hands-on design-and-build project lasting approximately 6 weeks, and involve activities related to designing, building, and evaluating devices. Workplaces were used to contextualize these unit projects in the curriculum, meaning that learners' projects were inspired by authentic workplace-related problems and scenarios, and introduced scientific concepts and technical practices used in workplaces to solve those problems. As written in a progress report, the designers wanted to "situate science learning in authentic workplace-related problems that are likely to capture students' interest, and that highlight the relevance of physics to their lives and potential future livelihoods." For example, in a unit on electricity and simple circuits, the project is to design, build, and test an electric circuit akin to a circuit controlling a defibrillator used in hospitals. The model defibrillator circuit project is thus situated in the field of biomedical equipment maintenance in hospitals, where technicians conduct critical mainte-nance and repairs on medical and related technical equipment, and need to understand scientific concepts related to electricity such as charge, voltage, and resistance.

Design-and-build projects (a form of project-based learning) were stressed so that learners would investigate and apply relevant physics concepts actively to solve practical problems, while also practicing engineering design skills such as measurement and analysis to construct devices, using specific metrics to test performance of the devices, and iteratively revising the devices. As curriculum writer P5 expressed, the designers aimed to foster "the kinds of understanding that come from actually working with, engaging with the ideas rather than just, you know, being exposed to the ideas so that the hands on and project-based stuff is important." Indeed, building devices such as prototypes of motion toys and defibrillator circuits was symbolic of this curriculum's pedagogy, as indicated by curriculum writer P4:

> This particular unit [on energy], and each unit in the [student resource] book, is designed to have students do science, not read about science. And it took the approach that kids would be acting like scientists, using the tools of scientists or technicians, and actually making something, building something, constructing something using engineering skills along the way.

Further, the designers intended to keep a minimal reading load because they wanted learners to explore scientific concepts actively through the unit projects, instead of simply reading about the concepts. As project leader P1 stated, they wanted to avoid teaching science as a "series of disconnected reading assignments." Curriculum writer P4 also expressed this vision in the interviews: "So that's our vision, that kids are learning, uncovering information for themselves, and not reading about it, not—We hate the idea of giving away the answer before they even have a chance to look at the concept."

The designers envisioned also reaching beyond classroom simulations of work-based projects to expose all learners to real-world models and applications of scientific knowledge in actual workplaces. They imagined incorporating relevant work site visits and learners' interactions with professionals. These visits were intended to help learners "see science in action"—to reinforce and enhance their understanding of how scientific concepts and technical practices introduced in the classroom were used to tackle problems in various occupational fields—and to learn about careers where science was a key component of workplace praxis.

Finally, the designers believed teachers were crucial in supporting learners with this curriculum, and they wanted teachers to guide learners in particular ways. Project leader P1 recalled that they wanted teachers to "elicit student ideas, to recognize that there's not necessarily one right answer; that a quote-unquote wrong answer can lead to further exploration and understanding." The designers imagined teachers would pose questions to help learners explore ideas and reflect on outcomes of their unit projects. Further, according to internal formative evaluator P6, their envisioned enactment emphasized classroom discussions, and the designers wanted the discussions to be "one of the central experiences that kids have, which is reflecting and then pushing their understanding through discussion."

Design Process to Develop EE In the analysis phase, the designers reviewed other science curricula to identify compatible pedagogical approaches, and to consider adopting or adapting suitable portions. In fact, they took this step before the curriculum was funded to formulate their initial vision for enactment in the grant proposal. This excerpt from the grant proposal shows the designers were inspired by a design-and-build project approach of another science curriculum developed previously at the designers' organization.

> '[In-house] curriculum has established an approach for motivating science concept learning through design-and-build challenges. We intend to use this approach within several … [present curriculum] units…. [In-house curriculum] is developing units—Simple Machines and Energy Audits—which are substantively related to the … [present curriculum's] areas of study. Supporting each of these design-and-build units are a collection of mini-challenges and mini-lessons that help students develop the conceptual understandings and manual skills they will need to solve the larger challenge'.

After receiving the grant, in the development phase, the designers continued to review existing science and mathematics curricula to learn from other approaches, and to refine their own vision for enactment. The team discussed strengths and limitations of different activities addressing content in those curricula, keeping in mind their own curriculum's aims and target audience. The designers noted various learning activities in this review: inquiry learning, data collection and writing, teacher-led discussions that solicited learners' ideas and engaged their interests, and project-based assessments that explicitly connected the science content to the assessments. Learners designed their own experiments in some activities, whereas other activities did not allow learners to design or share their experimental methods, were too prescriptive and not sufficiently investigatory. The review helped designers prioritize how they wanted to improve learners' experiences and teachers' practices. For example, they stressed project and performance-based assessments of learners' mastery of scientific concepts and skills, inquiry and applied learning, focusing on learners' interests, and teachers guiding learners to construct their own understandings of the concepts and skills, instead of providing answers to learners.

In the evaluation phase, the designers' vision for enacting workplace visits was refined iteratively through pilot testing in classrooms. Specifically, after they noted that learners valued the real-world nature of workplace visits, the designers decided to enact workplace visits earlier instead of later in the unit activities. This choice aimed to make the workplace connections more salient in the curriculum.

WC Consistent with the designers' vision, the unit projects were inspired by tasks and problem-solving practices drawn from various engineering and technological careers of potential interest to learners (see Table 6).

To evoke the workplace context in unit projects, there was a workplace-based storyline in the learner resource book, explicating how learners would perform the roles of engineers, designers, or technicians throughout the unit. The projects were written in the learner book and teacher guide as sequences of milestones. The milestones modeled phases of the engineering design process, leading learners from the initial problem to a final solution. The milestone tasks were embedded performance tasks, asking learners to demonstrate their understandings by applying relevant physics concepts and engineering practices to design, build, and test devices. Further, the activities built on one another and introduced content on a "need to know" basis, making certain concepts and practices prerequisites to attaining the milestone performances, and ultimately, the overall unit project.

The storyline contextualized learning activities and science content of unit project milestones in workplace-related scenarios, and flowed throughout a unit to tie the milestones and activities with relevant work contexts. The overarching storyline in the kinematics unit, for example, presents learners' roles as engineers working for a fictitious toy design company, and the unit project is to design, build, and test the performance of a Creepy Crawly motion toy, and to compare it to competitor toys in the marketplace. From the preliminary design to the final testing and comparative analyses of different toys, learners simulate the work of engineers in their classrooms. Table 7 shows how the project milestones in the Kinematic unit are contextualized in workplace-related scenarios, and model the engineering design process.

To guide learners through each activity of a unit project, there were activity sheets called "job sheets." The job sheets were consumable black-line master work records, containing procedures, design specifications and data, and questions to help learners reflect on scientific concepts behind the activities. Learners used job sheets to write their ideas and questions, record data after testing their designs, and to use representations like diagrams and graphs. The

Table 6 Curriculum units, projects, and relevant career contexts

Curriculum unit	Unit project	Career contexts
Kinematics	Construct and test a Creepy Crawly motion toy and compare it to other toys on the marketplace	Mechanical and design engineering
Forces and motion	Designing, planning, and implementing a performance test for All Terrain Vehicle tires for different conditions and types of motion	Mechanical and design engineering
Electricity and simple circuits	Design and build an electric circuit similar to the circuit controlling defibrillators used in hospitals	Clinical engineering, medical equipment maintenance
Generators and diodes	Modify the circuitry of a generator-powered bicycle light to improve its function	Automotive electrical technology and repair
Energy	Build, test, and operate components of a working r adio station to transmit notes from an instrument	Sound system engineering, Audio equipment design

Table 7 Mapping of project milestones to workplace-related scenarios and the engineering design process

Project milestone	Workplace-related scenario	Phases of engineering design process
1. Prepare a feasibility report of a Creepy Crawly motion toy, describing its performance, testing methods used, and suggestions for improvement.	The toy company's marketing team gives a work order with specifications and performance measures to construct and test a prototype toy. After initial testing, learners modify one characteristic of the prototype to improve its performance, and test the modified toy. Learners prepare a feasibility report for the marketing team.	Build solution conforming to design constraints; evaluate and redesign; communicate the solution
2. Prepare a comparative analysis report comparing the prototype toy to an ideal toy, and to the competitor's top toy.	Marketing team gathers specifications of an ideal motion toy from focus groups of typical consumers. Learners compare performance measures of their prototype toy to these specifications of the ideal toy. They also compare the performance of their prototype to the specifications for the competitor's top toy already on the market. Based on comparisons of their prototype toy to the ideal toy and the competitor toy, learners prepare a comparative analysis report for the marketing team, recommending whether the company should develop the Creepy Crawly motion toy.	Evaluate possible solutions; communicate
3. Prepare report reviewing the rest of the toy company's product line, including comparisons to the products' top competitors.	Based on the series of performance tests conducted before, the marketing team asks learners to test working models of other toys from the company that are market-ready. Marketing team also provides learners with motion graphs of the competitor toys. Learners create motion graphs for their company's toys, and compare these to the graphs of the competitor toys. Learners prepare a report of their analyses of specified performance measures for the marketing team.	Evaluate possible solutions; communicate

job sheets contained stepwise instructions for design and experiments, and were separate from the learner resource book, a non-consumable material.

Additionally, the learner book contained stepwise instructions for activities, and background information on physics concepts and technical practices was presented just-in-time via required readings. As described in a progress report, the book was designed as a resource guide for learners to periodically refer to during their unit projects, much like technical manuals used on the job, and unlike traditional textbooks. There was a reading tied to almost

each activity, explaining scientific and technical terminology needed to perform the milestones. In fact, the readings were intended as "concept builder" activities to help learners step back from design and experimentation, and focus on physics concepts and technical processes emerging in the course of their unit projects. Moreover, to avoid disconnected reading assignments as envisioned by the designers, the readings were assigned in the written instructions as required steps for completing the activities, thus making them purposeful to the unit projects. Their integration with milestone activities meant that relevant information had to be applied to complete the projects.

To illustrate, a milestone performance in the unit on electricity and simple circuits presented earlier asks learners to determine a safe level of current for the model defibrillator circuit, and to measure voltage and resistance in the model. To help learners understand and measure current, voltage, and resistance in performing activities for this milestone, the readings introduce information on how current moves in a circuit, on voltage, conductivity and resistance, and on Ohm's law.

Additionally, there were supports to enact workplace visits. At least one milestone activity in each unit project required learners to visit a relevant work site (or, if that was not possible, teachers could arrange classroom visits by workplace professionals). Curriculum writer P4 described the worksite visit in a unit on energy, where the project is to build a model of a working radio station with a transmitter and receiver:

> So there might be a trip to, in this unit, there's a trip to an audio specialist, where they visit someone either on their own or with their class, and ask them questions about science principles as applied to the workplace.

To guide learners' interactions with professionals, the job sheets contained questions on the functioning of physical devices related to the unit projects; on physics concepts and technical processes used on the job that related to the projects; and on the nature of tasks performed in those career settings. These questions were given to teachers, learners, and workplace professionals prior to worksite visits. The learner resource book also asked learners to review and discuss the questions in class, and to raise these during work visits.

Finally, aligned with the designers' vision for enacting the curriculum, the teacher guide contained supports to implement the design-and-build projects. For each milestone of a unit project, lesson-embedded text indicated when and how to introduce relevant scientific terms and conceptual information in the course of an activity, drew teachers' attention to learners' possible understanding of and difficulties with particular concepts and practices, and suggested ways to address those. These conceptual notes were separated from other lesson-specific teaching strategies. There were stepwise questions to lead whole class discussions and help learners step back from experimentation and design work and reflect on scientific principles underlying their work. Some questions elicited learners' initial understandings to lead into particular activities, others prompted interpretations of data collected during experiments, and yet others probed learners' reasoning about concepts arising during the course of the projects. The teacher-led discussions were thus crafted as complementary support to help learners make scientific meaning of their design and construction activities.

Design Process to Develop WC In the development phase, to determine appropriate levels of support and format of written materials for the present curriculum, the designers examined strengths and limitations of other written curriculum materials. They analyzed teacher

materials to determine how best to support teachers in responding to learners' thinking and in facilitating scientific practices, noting that some teacher materials explicated what teachers should say during instruction and separated it from conceptual notes, which helped streamline the text. On the other hand, some materials offered little support to teachers about possible learner responses, and ways to facilitate data collection and interpretation. Based on these insights, the designers specified providing text for teacher talk and separate conceptual notes, and recommendations in the teacher guide for the present curriculum to help learners draw conclusions from hands-on investigations and construct their own understandings of the scientific concepts and practices.

Additionally, the designers examined learner materials to determine how best to support learners to conduct and reflect on the results of their experiments, noting that some curricula did not adequately motivate learners with a need to know particular content, and there was little guidance for learners to produce written reflections about their experiments. Therefore, for learner materials in the present curriculum, the designers specified producing a non-consumable student book containing descriptions of activities, and references to worksheets where learners could record their thinking.

The designers found also that although some curricula presented learners' activities in real-world contexts, the materials did not always contain clear storylines to connect the activities and context explicitly. Therefore, in specifying their written materials, the designers emphasized that in the learner resource book, each unit would present a storyline that approached scientific concepts through the lens of a work challenge that may be addressed by professionals in various workplaces, and that the storyline would flow throughout a unit and link the activities together. The designers specified that each unit would include workplace scenarios to portray authentic situations where science concepts were applied and introduce problems that learners must solve.

To embed unit projects in suitable work contexts, the designers visited different workplaces and interviewed professionals like automotive alternator specialists, battery engineers, studio lighting designers, and light manufacturers. The purpose of these visits was to learn about actual workplace problems, processes, and science used on the job, and to guide the designers' choice of unit projects and milestone activities. The insights from these visits were critical to help designers "see the world through the eyes of technicians," and to ensure that the science content, storylines, and flow of project activities were contextualized in real workplace praxis.

A key challenge in structuring the units was integrating the unit project and milestones with the target science content. Specifically, the milestones had to be sequenced logically as steps leading learners from the initial problem to a final solution, helping learners complete the project. But it was also crucial to equip learners with the necessary scientific understanding to develop the final solution. Thus, the milestones had to address target scientific concepts and skills in a meaningful sequence. Therefore, to generate suitable unit projects, the designers themselves tested the unit activities conceptually, examining whether the unit projects would engage learners over several weeks, were sufficiently complex, and would require learners to apply target scientific content to complete the projects.

In the evaluation phase, there were two main sources of feedback to help the designers strengthen workplace connections and learners' understandings in the curriculum units. First, the funding agency's program officer drew the designers' attention to their target learner audience, with implications that workplace examples at the beginning of the curriculum units should not simply serve to elicit the learners' interests or provide an indirect way to understand science. Rather, the units should help the learners understand what technicians and engineers

actually do related to the unit content and activities. Based on this feedback, therefore, the first project leader emphasized making workplace storylines more salient in the units so that learners would better understand how technical tasks were performed in certain work settings, and what scientific ideas were involved.

Second, the designers used data from classroom testing to choose workplace-inspired problems with potential to connect to scientific understandings in the unit projects. See this excerpt from a progress report:

> We substantially modified the original forces and motion unit. The core project—analysis of actual bicycle accident reports—met with limited success. The pilot revealed that workplace supervisors did not adequately relate their work to scientific understandings or technological processes. Hence, we developed a new core project—design and implementation of a tire performance test. The field test indicates that the design engineers working with students in this project are indeed making the important connections between science and work.

Based on classroom testing, the designers also generated learning activities to address challenging science content. For example, the pilot test of a unit on kinematics revealed learners' difficulties with graphical representation. These skills were critical in accomplishing the unit's project of building a prototype motion toy, and generating and interpreting graphical representations of its performance data. Therefore, the designers rewrote the materials to include additional activities with graphing motion detectors to help learners produce and interpret graphs.

Based on how the designers steered their design process, and the insights they generated in developing a work-based science curriculum to promote deep understanding and rich performance in learners with different aspirations, the following section discusses implications of this work to guide other designers seeking to develop science curricula with similar goals.

Discussion

Guidelines for Work-Based Curriculum Design

This study presents a worked example of one high school physics curriculum which, through its work-based approach, aimed to promote deep understanding and rich performance in learners with diverse aspirations. The results show how designers generated learning experiences that are authentic, appealing, and rigorous for learners. It reveals their decisions and rationales. The answers to the research question about curriculum manifestations and design processes were summarized in Table 5. Based on these findings and in light of relevant literature, this section offers four key guidelines for the design of work-based curricula aiming to serve learners with varied inclinations. In addition to designers, the guidelines can also be useful to teachers wishing to adapt curriculum materials and customize experiences for their learners (Barab and Luehmann 2003; Squire et al. 2003). After summarizing the four guidelines and the key findings from which these were derived in Table 8, each guideline is elaborated.

Select for synergy To equip all learners with fundamental scientific knowledge, a science curriculum needs to address rigorous content, emphasizing core understandings of the target scientific discipline. Local and national frameworks of science educational policies will point

Table 8 Product and process guidelines for work-based curriculum distilled from this worked example

Guidelines for product/process	Based on product findings	Based on process findings
(i) Select for synergy. Ensure content is core to both the science discipline and workplace contexts	Students' learning focuses on applying standards-based key physics concepts and engineering design processes to solve design projects, and understanding relevance of science to many careers	Surveyed states to identify unit topics within potentially appealing career areas, with scope to address rich science, and in demand for work-based science curriculum Selected content standards from science frameworks Reviewed occupational information, matched selected occupations with science standards to choose unit topics and occupations Designers visited work sites to learn about workplace praxis
(ii) Align manifestations. Integrate the workplace context across IO, EE, and WC	Learning goals emphasize key standards-based physics concepts and engineering design processes that are integral to many work settings Curriculum enactment stresses on workplace-inspired, design projects in classrooms, coupled with learners' visits to relevant workplaces Written materials (work-based storylines and scenarios, job sheets, and supports for worksite visits) convey workplace connections explicitly and throughout units	Reviewed learner materials of other curricula
(iii) Provide specific teaching strategies and information on learners' understanding. Anticipate and attend to learning needs for the enactment of work-based science instruction	Curriculum envisions teacher facilitation in the form of eliciting learners' ideas, engaging learners with questions and discussions Guidelines for using scientific language, content, and instructional strategies, and for anticipating and addressing learners' alternative understandings	Reviewed teacher materials of other curricula
(iv) Prioritize evaluation concerns. Focus on reforms-aligned content, instructional supports, science and workplace connections, and timing of learners' workplace visits	Not applicable	External appraisal of content coverage, work contexts represented in written materials Internal testing of unit activities by designers to assess content coverage Classroom testing to revise instructional supports, select work-inspired unit projects with strong connections to science used on the job, identify appropriate timing of learners' workplace visits

IO intended outcomes, *EE* envisioned enactment, *WC* written curriculum

designers to key concepts of a discipline. To allow learners ample opportunities to investigate key ideas deeply and engage in the work of engineers and technicians, however, formulating a limited set of intended learning outcomes is recommended. Focusing on limited core science ideas instead of covering broad content is consistent with reform frameworks (e.g., NRC 2012). Furthermore, aligning the intended outcomes with science that is core to different work settings of interest to the majority of learners will contextualize the science in authentic, appealing, and rigorous contexts. This contextualization will help learners recognize how science is relevant to many careers that appeal to their inclinations, thus making science learning meaningful, as recommended by educators (Marginson et al. 2013; Osborne and Dillon 2008). Hence, it is worthwhile to take the time to explore and identify the content areas that align with both the discipline and the work context.

Based on the design process found in this study, three strategies are proposed to help designers identify science content that is rigorous as well as core to appealing workplaces. One strategy in the analysis phase is to gain insights into the needs of schools that wish to teach science from a career perspective. Specifically, designers may consider administering a needs assessment survey (McKenney and Reeves 2012; Edelson 2002) in secondary schools that (wish to) offer courses related to career areas that are of potential interest to learners with diverse inclinations. The data from such needs assessment can point designers to suitable work-based science content topics.

Next, in developing curriculum units, it is useful to compare content emphasized in science educational policy frameworks with the background science and technology knowledge needed in target careers. This requires designers to review thoroughly both policy documents from local and/or national levels (Krajcik et al. 2008; Rivet and Krajcik 2004; Songer 2006), as well as pertinent literature on different jobs in target career areas. In so doing, designers can generate specifications for including suitable career contexts in the curriculum.

Another measure in the development phase, which was salient in this study, is designers' visits to relevant workplaces. Interacting with engineers and technicians can give designers feedback on actual problems, processes, and science used on the job. This strategy for learning about science used on the job is comparable to the design processes of other science curricula. Specifically, designers of other reform-based science curricula seek input from scientists to learn about their authentic practices (Edelson et al. 1999), and to determine important scientific facts in science content areas (e.g., Songer 2006). The resultant insights from workplace visits can guide designers in choosing suitable problems that address important science content. Likewise, designers can ensure that the intended science content is integral to the kinds of careers that learners may consider after secondary school. Taking concrete steps to learn about different science-based work settings is crucial especially if designers lack adequate knowledge about work contexts that are appealing to learners with different inclinations, and that would also lend themselves well to teaching reforms-based science.

Align Manifestations To make reforms-based science appealing to learners with different inclinations, it is important to contextualize scientific concepts in problems and practices of actual work settings that are of potential interest to the learners. In so doing, it is recommended that designers use the workplace context across curriculum manifestations, planning intended learning outcomes and content, enactment of activities, and written materials that situate and organize target science content around workplace challenges. Using the workplace context consistently across curriculum manifestations will help align designers' ideals and written

materials (McKenney et al. 2006), and strengthen the desired connections between reforms-based science and workplaces.

Specifically, learning goals derived from curriculum frameworks should be aligned with science that is integral to real work contexts that designers wish to represent. This is critical to help learners understand how scientific concepts and practices are necessary to solve practical problems in workplaces. Further, in envisioning enactment of design projects to contextualize scientific knowledge, the projects should be based on key problems from a broad range of work settings of potential interest to the learners. The design projects should simulate different phases of real work praxis, leading learners from the initial problem to a final solution, and helping them see how they are working like engineers and technicians. As suggested in reform documents (Marginson et al. 2013; NRC 2012, 2013), engineering tasks and activities can promote problem-solving and applications to real-world contexts, and therefore need to be designed well to engage learners. Additionally, interacting with professionals using science in action can help learners appreciate connections between curriculum science and possible careers, also a key recommendation (Marginson et al. 2013).

Finally, it is recommended that written materials convey workplace connections *explicitly* and *throughout* unit activities to help learners understand how science relates to their potential careers and livelihoods. The storylines and work scenarios presenting learners' hands-on design projects in the learner materials of this curriculum, the job sheets guiding their investigations, and supports for workplace visits are examples of how text and language in a curriculum can be designed to evoke workplaces and to situate learners' experiences in concrete and authentic contexts. Thus, instead of simply presenting design projects as "workplace inspired challenges" at the beginning of curriculum units to merely elicit learners' interests, the written materials need to reinforce connections between reforms-based science and career contexts throughout different instructional activities. A detailed review of other curricula can shed light on what kinds of supports may be required to evoke workplaces in the written curriculum.

Provide Specific Teaching Strategies and Information on Learners' Understanding In developing a work-based curriculum, supporting teachers to enact work-inspired design projects merits special attention. This is because simulating workplace problems and processes, and connecting these to underlying scientific principles can be as unfamiliar to teachers as to the learners. Indeed, previous research suggests that science teachers may not always be familiar with enacting scientific practices (Knight-Bardsley and McNeill 2016; Krajcik and Blumenfeld 2006; Simon et al. 2006) or engineering design process (Mehalik et al. 2008), and may even hold misconceptions about authentic practices (Zangori et al. 2013). To simulate engineering design projects in the classroom, therefore, the authors recommend designing materials to include procedural supports (Roblin et al. 2018) as well as educative elements to facilitate teachers' enactment of the curriculum (Bismack et al. 2015; Davis et al. 2014; Davis and Krajcik 2005).

As manifested in this science curriculum, teacher materials may provide procedural supports to implement whole class discussions, like stepwise questions for eliciting and probing learners' understandings of scientific concepts, and tips on appropriate presentation of scientific language and content. Additionally, this worked example shows how teacher guides may also include educative supports to foster teachers' knowledge for teaching target science topics (Davis and Krajcik 2005). To this end, based on the present curriculum, the authors recommend embedding information to anticipate learners' possible (alternative) understanding or

difficulties in the subject, and suggestions for addressing these. These kinds of supports may help teachers implement key instructional activities stressed by educators, for example, performance tasks, open-ended questions, and discussions (NRC 2015; Tytler 2007). These kinds of supports have been shown to have positive impact on learner outcomes (Roblin et al. 2018). Here, too, a careful review of other curricula can generate insights into crafting appropriate materials for teachers.

Prioritize Evaluation Concerns In evaluating and iteratively refining a work-based science curriculum, designers are advised to focus on the following four areas distilled from the worked example presented in this study: coverage of (reforms-aligned) content, adequacy of instructional supports, connections between science and workplace significance, and timing of learners' workplace visits. Whereas the first two areas are common to good curriculum design, the last two are specific to fostering workplace connections in a work-based science curriculum. Together, they address curriculum manifestations (IO, EE, WC) and contextualization of science in work settings.

Additionally, designers may utilize different evaluation strategies to develop insights into these areas. For instance, external appraisal from experts (Krajcik et al. 2008; Thijs and van den Akker 2009) may shed light on the range of (reforms-aligned) science content that should be addressed. Further, designers may themselves conceptually test hands-on design projects and their associated activities to assess target content coverage (Kanter 2010), and to integrate target science learning goals within the structure and performance tasks of the design projects. This strategy may help ensure that unit project tasks are sufficiently complex and require learners to apply intended science content to solve problems. Also, testing the curriculum units with learners (Branch and Merrill 2012; Gustafson and Branch 2002) may reveal their difficulties with particular concepts and skills, and point to revisions in instructional supports.

With respect to workplace significance of the science content, pilot and field tests may indicate how well problems and processes simulated in the hands-on design projects connect to science used on the job, thereby guiding designers to select suitable work-based design projects with rich science content. Finally, classroom testing may yield insights into appropriate timing for enacting workplace visits during instructional activities.

Reflections and Recommendations

This research used a case study approach involving interviews and curriculum project documents, in which documentation prepared by the researchers was shared with the participants before the interviews. But the retrospective nature of the study necessitated participants to rely on their memories, particularly of the design processes, making it difficult at times to provide details of particular measures they took and/or insights they gained in creating and revising the curriculum manifestations. To address this limitation, the researchers extracted relevant information, wherever available, from project documents to confirm and extend the interview data, and to obtain new information. Although using multiple data sources yielded rich information, some phases of the design process for particular curriculum manifestations were not mentioned in sufficient detail in the interviews or project documents. As a result, these phases were not analyzed in depth or were excluded from the data analyses and findings. In the future, it could therefore be beneficial to study curriculum projects that are in progress. This may allow researchers to analyze products and design processes in more detail, and without needing to

rely on participants' recall of information. To study curricula in progress, researchers may consider gathering data through observations of the unfolding curriculum design process, in addition to analyzing drafts and prototypes of curriculum documents, and conducting interviews with designers to gather their insights on emerging design challenges and strategies.

Further, this study reveals the meticulous and time-consuming work that is involved in developing a science curriculum product that can yield positive learning outcomes. Indeed, high-quality curriculum design is a costly effort which requires considerable and continued funding (Burkhardt and Schoenfeld 2003). Further research on the outcomes of this process could help designers and policymakers alike. For designers, it would be useful to know: Do all the features of the written curriculum as described here contribute to positive outcomes? Equally? Or are particular curriculum features more regularly associated with positive learner outcomes? For policymakers, broader analysis of funded curriculum design projects and their outcomes could give important feedback on past funding support, and help identify key concerns to be taken up in future programs that support curriculum design.

Conclusion

By presenting a worked example of a high school physics curriculum which aimed to promote deep understanding and rich performance in learners with diverse aspirations through its work-based approach, this study is germane to international policy recommendations. It stands to support policy implementation indirectly, by offering insights to researchers, teachers, and other science educators who engage in curriculum design. Designing this kind of contextualized science curriculum is difficult, especially if designers are not familiar with ever-changing science and technology-based careers. The findings of this study can help designers think through and critique the intended outcomes, their vision for enactment, and features of the written curriculum, as well as the processes through which each of these are created. The guidelines derived from this study can help designers to focus on hands-on design projects that address a limited set of key reforms-aligned learning goals, contextualized in authentic work-inspired practices that are appealing to learners with a broad range of interests. Altogether, this study offers modest but crucial insights for designers creating curricula with workplace connections that can make science engaging and relevant to all learners.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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