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CRITERIA FOR THE SELECTION OF DEPLOYABLE AND RAPIDLY ASSEMBLED SRUCTURES

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ABSTRACT

In the last 20 years there has been an increased interest in building structures that change shape and form to adapt to different functional or weather conditions and respond to the continuously increasing demand for structures with reduced environmental impact. Current research in the field of Deployable and Rapidly Assembled Structures (DRAS) is focused on the classification of these structures based upon their features and properties. However, a methodology to assist a prospective user in selecting the appropriate DRAS is not available. In this paper parameters to be considered in the selection process are identified and grouped into general categories. Metrics to measure each parameter are also introduced. The usefulness of the parameters in the selection of a DRAS is demonstrated through a case study.

KEYWORDS

Structures, Deployable, Rapidly, Metrics

1. INTRODUCTION

A deployable structure is one that can be pre-assembled, relocated to a site, erected and used, then disassembled and moved to another site. The advantages of such a structure are significant when speed of transportation and erection are important requirements (Gantes, 1991). A rapidly assembled structure can be built on-site faster (due to pre-assembly or specific mechanical connections) than another structure built from component parts.

Deployable and rapidly assembled structures (DRAS) have been used throughout history and continue to be used today. Nomadic tribes crossing the deserts of Africa and American Indians roaming the plains of North America carried their living quarters with them as they traveled. Military forces of many nations mobilize with tents, weapon systems, equipment, and bridges that are mobile and able to be erected and disassembled expeditiously. Fabric structures used to house refugees from a south Pacific typhoon or families left homeless due to military conflicts are also representative examples of temporary structure needs.

Despite the wide range of potential applications of DRAS, a universally accepted method or approach for classifying deployable or rapidly assembled structures does not exist .due mainly to the diversity in their expected uses and their spatial, structural and mechanical conception. In the following paragraphs classification systems by Bulson, Escrig, Hanaor, and JOCOTAS are briefly presented because they are the most comprehensive ones, and they expose the diversity of the field and the difficulty in classifying a DRAS.

Bulson classifies rapidly assembled structures as hinged, pinned, clamped, sliding, or fabric, depending upon their anatomy and way by which parts of the structures are attached to each other (Bulson, 1991). Bulson defines a *hinged* structure as one in which rigid members are connected with pins and linkages or sliding connections which allow the structure to stabilize in the open position. The design of the joint is critical, since a joint can represent 20%-30% of the overall weight. *Pinned* structures are those in which the elements are transported separately and assembled on site using pins or bolts; military bridges are a well-known example. In a *clamped* structure such as scaffolding, elements are single bars or tubes connected by clamping elements to form loose frames. *Sliding* structures have members that deploy from a stowed configuration t by sliding against each other. The pins, bolts or clamps of the previously discussed categories are replaced by telescoping hydraulic or pneumatic components. *Fabric* structures, are defined by the dismantling of flexible, foldable materials for ease of storage and transportation. Pressure (often air) is introduced to achieve structural integrity of items like parachutes and balloon structures. The greatest benefit from using a fabric structure is the low ratio of stored volume to deployed volume; a packed tent occupies just a few percent of its erected volume.

Escrig, a leading researcher in the field, describes eight distinct types of deployable structures apparently based upon a combination of material, shape, and method of deployment. *Tensile folding structures* rely on the tension of the structural components to support the structure and give it shape. *Tensegrity roofs*, the second type, are a specific application of tensile structures. Tensegrity structures (including tensegrity roofs) are self-supported, internally pre-stressed structures with discontinued compression: parts under compression are not in direct contact with one another and are held together by intermediate pre-stressed members. A *retractable roof structure* (third type) "is the type of structure in which a part of, or the entire roof can be moved or retracted within a short period of time so that the building can be used with the roof both in an open state or a closed state" (Ishii, 2000). A *membrane* or *fabric* that is foldable is the fourth type of structures classified by Escrig. What distinguishes this type from being included in the retractable roof category is that the structural components are "hinged pieces that fold and extend like an accordion" (Escrig, 1996). A structure that opens and closes by making use of a sliding mechanism on a mast is considered an *umbrella structure* (fifth type). In Calatrava's *mobile structures* (Escrig's sixth type), some space defining elements are lifted and get relocated to another position, creating a different spatial geometry and functional definition. Similar to the body of an animal, these deployable structures appear as if they have bones, muscles, and tendons, which produce smooth flowing movement across their ranges of motion. *Lifting structures* (seventh type) are placed at ground level and then lifted into final position by a jacking system. Escrig's last type, referred to as *deployable structures* includes collapsible grids, un-hitched joints grids, and X-frame structures. These deployable structures have members joined at their ends in a geometry that allows for their extension and contraction.

Hanaor's system of classification, the third considered in this paper, groups structures according to their structural-morphological properties and kinematics of their deployment, meaning that the organization is done with respect to how the structure acquires its shape and strength and how the structure is deployed (Hanaor, 2000). *Lattice* or *skeletal* structures and *continuous structures*, including *stressed-skin* structures, are the two main divisions of deployable structures based on their structural-morphological properties; Hanaor does recognize that hybrid ones exist, but keeps them divided by handling their components separately. Rigid links versus cables and fabrics (deformable or soft components lacking flexural stiffness) are how Hanaor organizes the kinematic categories. The significant aspect of Hanaor's work is that it shows that deployable structures must be considered in terms of their structural form together with their means of deployment. A retractable roof is a skeletal structure whose movement is done with rigid links. A tensegrity dome is also a skeletal structure, yet cables, which by definition are deformable, control its motion. A balloon frame is deformable and gets its shape from a stressed-skin covering.

The Joint Committee on Tactical Shelters (JOCOTAS), chartered by the U.S. government, defines a tactical shelter as "a highly mobile, transportable structure designed for a functional requirement that provides a live-in and/or work-in capability (JOCOTAS, 2000)." JOCOTAS classifies tactical shelters into the three categories of rigid wall, soft wall (military tent), and hybrid.

In table 1 below the four different classification systems are compared. Bulson's is the most specific of the four systems, and is only concerned with the type of joints in rapidly assembled structures. Efficiency of deployment is taken into account in his evaluation of different types of structures. Escrig classifies deployable structures according to the materials used to construct them and the method of their deployment. Hanaor also considers deployable structures, and organizes them by structural form and kinematics of deployment. He is mostly concerned with their structural efficiency and performance. JOCOTAS is only concerned with military shelters, and classifies them according to their shape and materials.

Table 1: A Comparison of Existing Methods of Classification

Classifier	Type of Structure	Classification Method(s)
Bulson	Rapidly Assembled	Joints
Escrig	Deployable	Materials
Hanaor	Deployable	Morphology Kinematics
JOCOTAS	Military Shelters	Use Materials

It becomes obvious from the comparison of the four classification systems that the design or selection process, that is finding the right DRAS for a given set of conditions, is not a simple matter. The classification systems described above can only help if selection criteria or parameters are established. Four parameter groups, as well as logical measurements or metrics for each parameter have been identified and are described in the following section. In section 3 a case study is used to demonstrate the usefulness of these parameters in choosing the appropriate DRAS from the different options described earlier.

2. SELECTION PARAMETERS

DRAS structures have been classified by their intrinsic properties with no or little regard to the needs of the users. In this chapter parameters are introduced that, when considered, can lead to the best application of a DRAS in meeting user needs and satisfying requirements of the function and location of the facility. A total of 58 parameters that fall into four categories, that is *function and use* parameters, *contextual response* parameters, *material properties and methods* parameters, and *financial* parameters are proposed for determining the appropriate deployable and rapidly assembled structure. A detailed discussion of selection parameters can be found in Donley's thesis (Donley, 2001).

In table 2 a summary of the function and use parameters, which address the prospective users of the structure, the reason for building the structure (user needs) as well as aspects of the function and use of the structure that are particular to DRAS, such as speed of erection and transportability, are presented. In order to address some of the use and function parameters, such as the number and size of openings, an analytical approach is required, which is the standard procedure for the design of conventional structures, and which allows for a thorough understanding of the intended use of the structure and the functions that will be performed in or around the structure.

Table 2: Function and Use Parameters

Function and Use	
Item	Unit of Measure
Basic User Needs	
Use of structure	cu ft, sq ft/person
Persons living and working in structure	number of pers
Security/Accessibility concerns	Y / N
Frequency of erection/disassembly sequence	every # of days
Desired erection, disassembly time	days
Expandability	Y / N
Ability to be integrated with existing structure	Y / N
Life span for application	months
Reuse	Y / N
Systems Integration	
Natural lighting	Y / N
Ventilation	H / M / L
Need for openings	#, proportion of height/width to size
Acoustical Issues	dBs
Electrical issues	KWH
Water/sewage issues	Gal/Day
Refuse	Lbs/Day
Health Considerations	Y / N

Table 3 contains the parameters which take into account the built and natural context in which the DRAS will be erected. Cultural considerations, climatic conditions, and physical characteristics of the site, such as grade, are included.

Table 3: Contextual Response Parameters

Contextual Response	
Item	Unit of Measure
Cultural Dependence	H / M / L
Climatic/Microclimatic Considerations	H / M / L
Area preparation/Site work/Foundation required	W-H
Grade of site	% slope
Limited or specific footprint	Y / N
Contamination/Hostile environment	Y / N
Range of internal temperature of structure	degrees F
Site Accessibility	H / M / L

Table 4 addresses the material properties of the structure and methods of assembling, erecting and deploying DRAS. The section titled *Geometric and Physical Properties* contains parameters dealing with the size, weight and design criteria, including structural performance issues, such as required performance in earthquakes. Parameters that address maintenance considerations are also included in this section. The *Erection and Collapse Procedures* section is concerned with the personnel who will assemble the structure and the mechanical methods required.

Table 4: Material Properties and Methods Parameters

Material Properties and Methods	
Item	Unit of Measure
Geometric and Physical Properties	
Structural system	self-supported or skeleton
Minimum and maximum size of structure	SF / CF
Minimum and maximum size of usable space	SF / CF
Equipment integrated into structure	Y / N
Fire protection	H / M / L
Storm considerations	H / M / L
Seismic/Volcanic considerations	H / M / L
Windloading	H / M / L
Snowloading	H / M / L
Mobility of structure in compact form	H / M / L
Weight and Volume	Lbs / CF
Off the shelf or engineered for this particular use	Y / N
Delivery time	days
Capable of withstanding long term storage	Y / N
Maintenance required during storage	W-H
Maintenance during deployment	W-H
Reconstitution effort	W-H
Part replacement	H / M / L
Erection and Collapse Considerations	
Safety of workers and public	list each item/area
Project Management	H / M / L
Plans and Specifications	H / M / L
Float	H / M / L
Level of assembly	H / M / L
Collapse method	H / M / L
Work hours to erect/disassemble	W-H
Skilled & non-skilled workers required	# of workers
Special tools & equipment required	Y / N

Table 5 deals with the financial aspects that address the life cycle cost of the structure under consideration. Several of the parameters in this section are specific to DRAS such as disassembly cost or storage cost. Maintenance cost includes both repair costs and costs for cooling and heating the structure if applicable.

Table 5: Financial Parameter

Financial	
Item	Unit of Measure
Material/Purchase cost	$
Deployment cost	$
Erection cost	$
Maintenance cost	$ / month
Disassembly cost	$
Reconstitution cost	$
Storage cost	$ / month

The parameters presented are general enough so that, in designing a facility and addressing the needs and requirements of a user, additional parameters could be considered. Furthermore, the tables are not intended to be used merely as check lists. Rather, the situation must be evaluated to determine which issues are critical, important, ordinary, or can be ignored or ruled out. The value in presenting such a comprehensive list is in providing a starting point from which the facts can be researched and a workable result produced.

3. CASE STUDY

Assume that a large southern U.S. city holds annually the State Fair and has a need of 12,000 SF of space for educational activities broken down as follows: classrooms (5,000 SF), multi-purpose area (1,000 SF), play area for children (2,000 SF) and administrative area (4,000 SF). The promoters have considered using a single or multiple DRAS to bring additional creativity to the fair and showcase new technology and the talent of local construction professionals.

Initial analysis shows that one of two basic approaches may be taken: one large structure may be built with internal divisions segregating the activities, or smaller structures may be built for each activity which are connected by sidewalks or breezeways. Figure 1 shows this graphically.

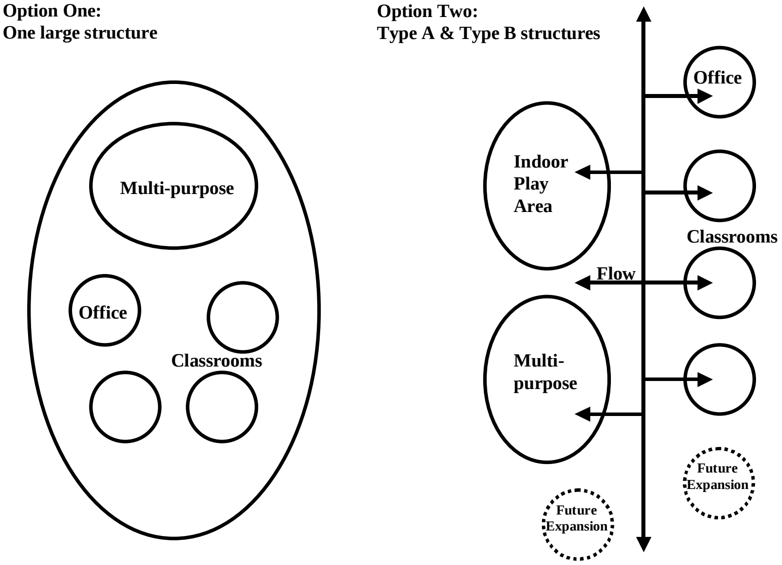

Figure 1: Two Options of Meeting Activity Requirements

In this scenario, fact gathering has determined that goals go beyond the use of the structure and issues like project visibility, funding options, appropriate site features, and site analysis of possible locations need to be taken into account. These goals must be understood before the specific project needs are determined. Key issues identified are the desired erection time of two weeks, the life span of two months, the possibility of reuse of the structure(s) in the same or a different location, natural ventilation and lighting, and acoustical concerns. A DRAS structure allowing lots of sunlight and natural ventilation is highly desirable. Each of the parameter tables presented in section 2 have been expanded to include additional columns addressing the two options. They can be found in Donley's thesis (Donley, 2001).

Five of the function and use parameters identified as particularly important are the erection time, life span, reuse, ventilation/lighting, and acoustical considerations of the structure. Two of these, erection time and ventilation/ lightning, point to specific types of structures. A *scissor structure* could be erected in very little time by extending its members as compared to the erection of a pinned structure, which must be built from component parts. The scissor structure could also be dismantled and erected at another location, making reuse easier, which satisfies another requirement. A *tensile fabric structure*, as described by Bulson and having openings that allow natural light to penetrate and air to flow freely, would be an alternative to a solid walled building. However, such a structure would not meet the requirement to separate the various activities acoustically and therefore could not be used.

The main issue of importance from the contextual response table is the temperature limits of the indoor play area; while this does not point to any specific type of structure, a structure having a retractable roof may be useful. The structural system and size are the important geometric and physical parameters. The possibility of hail may dictate that hard materials be used; the need for a large covered space will limit the number of DRAS possible. Safety of workers, the public, and children using the facility is the significant concern during erection and collapse, yet this does not limit the use of any type of structure. Financial aspects are not addressed.

All of the parameters presented are not applicable in every scenario, and some simply are not as important as others. Some of the important parameters point to a particular type or category; other ones rule out classes of structures. This elimination can be just as effective in determining the appropriate structure because it removes possible solutions and narrows the field of choices. A retractable roof provides flexibility but additional maintenance is required on the joints and availability of parts may be low. An inflatable structure would get attention, but relies on a compressor to maintain its integrity, and generally has a short life span, both in storage and when deployed. The strengths and weaknesses of each type of structure must be known, along with the specifics of its deployment, so that the right structure can be chosen.

While no definitive answer can be given in the case study presented, it can be summarized that an off-the-shelf design of a pre-assembled structure, as classified by JOCOTAS, would work in this situation, but would not meet the organizers' need to showcase new technology and novel ideas. Sufficient time exists to design and construct a reusable tensegrity structure. Similarly, a scissor structure could be designed to meet the needs of the organizers and users. A reciprocal frame building, as defined by O. Popovic et al., who invented this new type of structure (Popovic et. al. 96), and falls into Hanaor's classification of a lattice structure with rigid links, would be novel at the fair and attract desired attention.

4. CONCLUSIONS

Existing classifications of deployable and movable structures by Bulson, Escrig, Hanaor, and JOCOTAS who divide them into different categories, depending upon the material, shape, motion, and joints of the structure, underscore the complexity of selecting the appropriate DRAS for a particular use. The objective of this initial investigation of deployable and rapidly assembled structures was to facilitate the selection process by identifying the appropriate parameters than need to be taken into account when choosing a DRAS. Four large parameter groups were identified, and logical measurements for each parameter were proposed. The usefulness of the parameters was demonstrated through a case study.

Many areas worthy of exploration remain to be investigated. In follow up work the parameters will be ranked according to their relative importance with respect to the given situation. Consideration should certainly be given to risk analysis of each type of structure with respect to various environmental and situational conditions. A computer-based application could be created to present the parameters, collect the data, and assist the user in the logic of choosing a particular structure. Thus, solutions for possible scenarios may be prepared ahead of time and be available for review by interested individuals.

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