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Conceptual Specification of Forest Residues Balers using the Appreciative Design Method

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Abstract.

Baling of fine forest residuals such as tops, branches, and thinnings is expected to reduce the cost of collection, transport, and processing. Baling may enable economical access to currently stranded biomass resources that are inaccessible to large in-woods grinders and specialized chip hauling vehicles. The technical feasibility of baling logging slash branches and tops has been demonstrated with an engineering prototype biomass baler. Design and specification of full-scale operationally efficient balers for use in forest settings entails achieving objectives and constraint sets held by many stakeholders such as landowners, operators, contractors, manufacturers, etc. This paper details a disciplined and structured Appreciative Design Method used to establish engineering, functional, and configuration specifications for an entirely new class of woody biomass balers.

Keywords. Forestry, mobile equipment, biomass baling, forest residuals, engineering design, transportation, forest operations, bioenergy, biofuels

Introduction

We previously developed the case for woody biomass balers as a solution to the need for cost-effective collection of woody biomass from urban vegetation management projects, wildfire protection thinnings, and similar highly dispersed sources (J.H. Dooley, Fridley, DeTray, & Lanning, 2006; J.H. Dooley, Lanning, & Lanning, 2011; J.H. Dooley, Lanning, Lanning, & Fridley, 2008; J.H. Dooley, Lanning, Lanning, Broderick, & Fridley, 2009). A full-scale engineering prototype was designed and built to conduct field studies across a range of sites. The prototype enabled validation of platen pressure-bale density relationships, evaluation of productivity by work element time, and a demonstration platform for bale producers and users. A limitation of earlier work is that it focused on urban and suburban woody biomass sources. Forest biomass was only evaluated in the context of wildfire protection thinnings and vegetation management activities.

The current project reported in this paper extends that work to the context of baling forest residuals (aka logging slash) in connection with conventional forest harvest operations. The motivating belief was that baling would enable cost-effective recovery of woody biomass from "stranded" landings that are inaccessible to large in-woods grinders and specialized chip trailers. If additional woody biomass could be collected and economically delivered to centralized processing sites and regional biomass users, then forestlands would be made safer from wildfire and have more productive area where piles are removed. Local communities would obtain access to additional woody biomass to support bioenergy and bioproduct enterprises, and economic activity would increase.

This project is conducted within the scope of a Biomass Research & Development Initiative (BRDI) contract awarded by U.S. Department of Energy to Humboldt State University (Agreement No. DE-EE0006297). The forest industry in the western United States is phasing out slash pile and broadcast burning due to concerns about smoke, risk of fire escapes, and thermal effects on soil quality. The alternatives are to chip and scatter the material back across the harvest unit or to haul the slash off the site in either whole or ground form.

Figure 1. Forest residuals pile and dispersed slash after logging on private forestland near Arcata, CA.

When markets do not exist, the problem is one of off-site disposal. In the disposal case, the objective is to minimize current costs for collection, transport, and disposal or below-cost sale (reduce the negative value of the material). A cost-minimization strategy may include production and sale of unprofitable materials and products that can be made from the residuals, such that the enterprise-wide effect is less costly than straight disposal. In any event, the operational objective of "slash removal as a disposal problem" is to minimize the cost of handling and transport to "somewhere off the forest." For the disposal case, baling reduces the cost of transportation and handling compared to loose bulk material.

A premise of the BRDI project is that value-added markets may be created for biochar, torrefied coal-replacement fuel, and energy pellets as an alternative to outright disposal of forest biomass. An objective of the project is to conduct a technical, economic, and sustainability (life cycle analysis) assessment of new methods to collect woody biomass from logging sites in the western United States. The forest operations team explored the value of sorting slash piles to separate poles and pulpwood from the branches and small top material. The poles and pulpwood could be economically hauled to centralized chipping sites and converted into relatively clean chips for value-added uses. Sorting reduced the volume of remaining biomass, and is assumed to enable more-effective baling of remaining tops and branches into high density modules for transport, storage, and centralized grinding into thermal fuel or mulch.

The problem of using woody biomass balers for collection of forest residuals is quite similar to that of urban chipper-replacement balers at many levels. Both contexts have an objective to minimize the cost of collection and transport as part of a “disposal” operation. Market values for woody biomass are currently not sufficient to cover all costs and reasonable profit for participants in the collection and logistics system. However, woody biomass removal from urban landscapes and from completed logging sites is a management decision or policy of public and private landowners. Thus, successful specification and design of balers for forest residual collection is inevitably value-laden and stakeholder driven. In our case, success will be measured by the rate of adoption of baling by forest operations contractors. Technical design is not trivial, but is amenable to conventional application of engineering science and data.

Forest Concepts has a long history of developing new machines and products that have achieved market success, in large part due to the use of our innovative Appreciative Design Method for engineering projects. The balance of this paper summarizes how we apply the method to the problem of specifying woody biomass balers for collection of forest residuals biomass.

Appreciative Design Method

The Appreciative Design process was developed between 1985 and 1995 to enable disciplined engineering and design of messy problems that have both social and technical elements (James H. Dooley & Fridley, 1996, 1998b). Appreciative Design is a structured process to search for a best set solution to technical and organizational problems. The Appreciative Design process is a significant extension of the hierarchical axiomatic design methodology of Suh (Suh, 1990, 1995) and includes many features of the Soft Systems Methodology developed by Checkland (Checkland & Scholes, 1990).

Suh’s structure and optimization methods (Suh, 1990, 1995) are particularly well suited for addressing the messy problems that are common in industry and the natural resource fields. Suh’s approach is based on a set of design rules. Our implementation of Suh’s approach adds some important structure and detail, as well as provides an easily followed hierarchical tracking of information, alternatives and decisions. The hierarchical structure allows reviewers, decision-makers and others to easily follow the history of decisions made throughout a project.

Suh’s design principles are expressed in terms of a decision logic that includes functional requirements, design parameters and constraints (Suh, 1990). Functional requirements (FRs) are design objectives cast in solution-neutral and independent statements. There is general consensus that problems are best defined when the objectives are framed by what is to be achieved by the project rather than by how needs are to be met (Love, 1980).

Design Parameters (DPs) are either brainstormed alternatives or calculated specifications that become features of a solution. Brainstorming, ideation and other methods of creating or searching for alternative solutions are well understood by engineering professionals, educators and students so did not need to be included in the process model.

Constraints (Cs) are objective statements and mathematical relationships that set bounds on the range of DPs that are acceptable. Constraints provide limits on the how, what, when, where and why of the design solution. Constraints are most often used by designers as criteria to sort alternative DPs into those which are acceptable and those to be discarded or reworked. An initial set of constraints typically is drawn from conversations with the client and all relevant stakeholders. Constraints can also be found through exploration of the laws of nature (e.g., $f = ma$, $\sigma = mc/I$), laws of humankind (e.g. codes, laws and regulations), cultural norms of the organization (e.g., policy and design manuals), and norms of the community (e.g., codes of ethics). In all cases constraints must be linked to a “constraint owner” in order to make them relevant to the problem at hand (McIntyre & Higgins, 1989). The constraint-owner linkage provides relevance to a constraint and its source.

The problem of designing new equipment such as biomass balers begins with listening to the project initiator/sponsor’s story about the need or opportunity and carefully documenting his/her objectives. It is of particular importance to understand and document what constitutes success in the worldview of the sponsor.

Scenario and Motivating Objectives

The case for designing an entirely new class of woody biomass balers for the forest industry is built from a complex set of business, public policy, emotional, and economic needs, wants, and concerns held by forest landowners and managers who initiated this project. Buried in their stories and expected operating scenarios are clues to the functional objectives and constraints that will frame subsequent technical design and engineering.

As noted earlier, forest landowners are highly motivated to remove forest residuals from the landscape to increase productive land area and to reduce the risks of wildfire or escaped slash pile fires. The current value of woody biomass for thermal bioenergy is insufficient to cover the direct costs of collection, grinding, and transport under any scenario. Therefore, new markets need to be developed to help offset the costs to landowners for biomass disposal. The BRDI project is evaluating processing and conversion of forest residuals into biochar, torrefied coal-substitute fuel, and compressed fuel bricks or densified “white” pellets for use in residential and commercial heating systems.

The project team developed an operating scenario that has the following elements.

- Logging slash is sorted at landings into poles/stem segments that can be chipped into clean feedstocks and other material including tops, branches, and brush that must be ground or baled into low-grade products or thermal bioenergy fuel.
- Pole and chunks are hauled from the forest in dump trucks or hook-lift containers to central processing yards.
- Tops, branches and brush is either ground on-site using horizontal grinders and hauled in chip trailers, or is baled for in-woods transport.
- Bales, chips, and/or ground material is delivered to a central storage and processing site near the forest where the material is redistributed to customers or converted into value-added products such as biochar, torrefied pellets, or densified fuels.
- All thermal and electrical energy for operating processing and conversion equipment at the central yard is generated on-site from combustion and/or gasification of residuals.

A limitation of conventional in-woods grinding systems is that large landings are needed to support grinders, support equipment, and a fleet of chip vans. Current practices involve establishment of in-woods grinding sites that are maintained for several years to support harvests in a 2-4 mile radius. Once established, much of the forest residuals must be hauled in forwarding trucks from dispersed slash piles and landings to the grinding site. Costs become prohibitive when landings are small or the haul distance exceeds about two miles (Bisson, Han, & Han, 2013).

A consortium of landowners, contractors, foresters, and forest operations researchers came together under the BRDI project to define and test new concepts that have the potential to reduce costs, enable recovery of more biomass – particularly from stranded landings, and decouple the removal of forest residuals from the landscape with grinding or subsequent conversion into products or fuels. Earlier efforts to decouple collection from processing used hook-lift containers (Han, Halbrook, Pan, & Salazar, 2010). Recent work considered the economics of forwarding with off-road dump trucks (Bisson et al., 2013). Both of these earlier efforts were limited by the low bulk density of forest residuals. Improved logistics for collection and hauling equipment has also been quantified (Zamora-Cristales, Sessions, Murphy, & Boston, 2013). The Zamora-Cristales study details the difficulty of coordinating in-woods processing and hauling operations.

The present BRDI project includes exploration of baling as an alternative that has the potential to decouple biomass collection from hauling. Bales may also substantially reduce the transport costs and number of trucks/containers needed for transport of poles and chunks. However, baling adds its own costs, fossil fuel consumption, and productivity to be factored into deployment decisions.

High-Level Identification of Stakeholders and Constraint Owners

Social network analysis can be used to map the connections between networks of individuals or firms, particularly where very large numbers of participants exist and the mechanisms by which they influence and are influenced are not clear. We previously applied social network analysis in the forest and natural resource arenas successfully (James H. Dooley & Fridley, 1998a). The BRDI baler project will use a composite scenario where sponsor’s objectives can be described. We can also identify the key stakeholders and constraint owners surrounding a typical forest operations activity and biomass supply chain. It is useful at the outset of the specification and design effort to list as many of these people as practical, identify their individual objectives and constraint sets, and necessary levels of communication and engagement during the design process.

For the purposes of this paper, we will show a subset of the high-level stakeholders and constraint owners who drive the configurations and specifications for a new generation of forest biomass balers. We begin with the land owner or property manager and end with central storage and grinding site operators.

Table 1. Stakeholders and Constraint Owners

Stakeholder	Objectives	Constraints
Landowner / Manager	Remove excess biomass from landings and piles - Reduce fire risk - Increase productive land	Minimize cost Minimize environmental risks from compaction, disturbance, etc. Remove all designated biomass from the site including branches, tops, chunks, and poles Assure that all operations, environmental effects, and workers are safe, and comply with all local, state, and federal regulations
Forester / Logging Supervisor / Forest Area Manager, …	Achieve landowner objectives and constraints in a cost-effective manner	Create a baling solution that does not require additional grading, roadwork, or new landings beyond those put in for the logging operation At a minimum, recover all of the bulky branches and tops from landings and roadside piles. Poles and chunk-logs may be hauled in other types of trucks Minimize the delivered cost of baled biomass from the forest to centralized storage sites on or off-forest Create bales that maximize the potential for positive revenue to the firm. If markets exist for baled biomass, ensure that baled forest biomass will not be rejected by customers
Forest Operations Contractor / Equipment owner	Reliably achieve profit objectives - Costs of ownership and operation are as advertised and expected	Equipment can access all required sites, including formerly stranded sites at minimum transport and hauling costs Assume that a grapple loader will be on-site to move raw materials, sort biomass poles and chunks, and load bales Minimize cost Maximize productivity Minimize crew Be safe for operators, mechanics, support staff Avoid fire risks Meet or exceed all regulations for highway transport, exhaust spark arresters, OSHA, DOL, etc. Cost and availability of consumables (twine, fuel, lubricants, etc. are predictable)
Forest Operations Supervisor/Lead	Balers are appropriately sized for the materials and production rates required by the Forest Operations Contractor/owner - Daily and weekly	Equipment is safe, not a fire hazard Minimal or no need for pre-slashing of biomass or human ground crew – avoid human chainsaw operators or humans within swing of grapples or safety zone

	production goals can be met - Baler fits into a matched equipment and human system of loaders, trucks, trailers, and balers	around machine Baling can be conducted during all weather conditions Baler operation meets all fire and safety regulations (spark arrester, etc.) Daily maintenance is not time-consuming Fuel is same type (diesel) as other equipment on the site Lubricants are the same types as already in use for other equipment Operation is not difficult to train or supervise. Fundamentals of operation are intuitive and common across range of baler models in the fleet Moving or relocating baler in the forest or around a landing is fast and easy Bales are formed with good integrity and do not have to be redone Consumables (twine, etc.) are easy to handle and store on-board or in support vehicle Mechanical breakdowns are rare and easy to fix with minimal lost production Bale handling logistics does not create a bottleneck on the site or roads
Baler Operator	Bales can be produced at desired production rates and quality	Noise, dust, heat, rain, snow, and other environmental nuisances are controlled to tolerable levels Equipment is inherently safe or safe operation is attainable throughout the work day Bale making is not too strenuous – automation is preferred Controls and control systems are intuitive
Bale Hauling Contractor	Maximize payload on forest roads Enable rapid loading and unloading	Bales fit on highway legal truck and trailers - 96 inches wide, 104 inches high Bale shedding is minimal until truckload is tarped Higher bale density enables shorter trucks and trailers
Central storage and grinding site operator	Maximize storage density in bale-yard Enable handling with conventional hay bale squeezes and stackers	Bale dimensions are compatible with 500-1000 hp horizontal grinder infeed without cutting twine Bales maintain integrity as they dry-down during long-term storage

		Fewer, larger bales are better to reduce handling time and costs Need to be able to grind and haul at least 400 green tons per 10-hour day Twine material (poly, sisal, wire, etc.) are either compatible with ground-feedstock uses or are easily removed at grinding
Central small-scale conversion facility site operator	Maximize storage density in bale-yard Enable handling with skid-steer loader one bale at a time	Minimize required bale handling capital for unloading, handling, and feeding bales Minimize land area used for bale storage Maximum bale height of 34 inches to enable grip by skid-steer loader bucket with thumb Maximum green bale weight of 1,250 lb to enable safe lifting with skid-steer loader Bales maintain integrity as they dry-down during long-term storage Bale dimensions are compatible with 150-400 hp horizontal grinder infeed without cutting twine Need to process only enough material for next 1-2 days of conversion – typically 10-50 tons per day Twine material (poly, sisal, wire, etc.) are either compatible with ground-feedstock uses or are easily removed prior to grinding
BRDI Project Leadership	Recover biomass for highest value uses - Poles, pulpwood, and chunks are to be separated for chipping to clean chips - Branches, tops, and brush are to be baled	Assume that slash piles are sorted prior to or at the time of baling by a grapple loader In-woods drying of biomass prior to baling or hauling logs is preferable to processing green
Guiding Engineering Data		From earlier baling research: - Loose density of tops and branch piles is approx. 3 lb./cu.ft. (green) - Bales can be compacted to up to 25 lb/cu.ft. (green) with reasonable energy input - Moisture content at time of baling can range from 25 – 55 %(wb) - Biomass is in piles or windrows that must be picked up with grapples and cannot be picked up with a header on a moving baler - Forest residuals tops and branches range in length up to 20 feet, with a mean length approximately 8 ft.
Guiding Forest Operations Data		Assume that the number of slash piles is approximately 100 per 40 acre harvest

		unit. (Oneil & Lippke, 2009). Large piles contain approximately 140 green tons and small piles contain 0.5-3 green tons Assume that baler does not have to leave the road for highway legal balers

The above scenario and stakeholder table provides important clues and guidance for designers of forest balers. Separation of objectives and constraints into columns clearly focuses attention on what is important to stakeholders in their (almost) natural language. Engineers can then begin to translate objectives and constraints into technical terms and equipment specifications. Future design decisions can be evaluated and scored as to how strongly they achieve the stated objectives and the degree to which they comply with stated constraints.

Top-Level Functional Requirements and Constraints

Careful review of the stakeholder table suggest that a new class of forestry balers must be agile, productive, safe, and fit into both existing and conceptual operating scenarios. There are also two extremes of productivity needs. In one case, landowners and managers want to recover woody biomass only from sites and landings not accessible to conventional large grinding and hauling operations. This means that a baler system must be able to move at low cost to parts of the forest distant from main roads and grinding sites, and process site-specific volumes that are too small to economically forward to main grinding sites. The other case is to potentially replace in-woods grinding entirely by baling and hauling everything (except the poles and chunks) to a large central storage and processing site.

We also see that the operators of central storage and processing sites have divergent needs for bale size and handling equipment. The large central grinding site needs very high productivity at production rates of at least 400 tons per day, while the small conversion site must be economical at 20-50 tons per day.

Although not part of the stakeholder table, the baler manufacturer desires to produce and sell a complete line of biomass balers that meet the needs of a range of prospective customers and users. Since there are no constraints on meeting the needs of separate operating scenarios by two baler “models,” we are making that choice. Our engineering product design experience suggest that it is unlikely that a single baler can fully meet the objectives and constraints of both small volume systems and high volume systems. That said, there are many common specifications and features, as well as engineering science/data that are common across a full baler product line.

The two models of baler now can be defined in natural language terms to guide the next rounds of technical design and specifications.

Table 2. High-level baler model descriptions

	High-Capacity Forestry Baler	Agile Small-bale Forestry Baler
Bale size	As large and heavy as can be handled by hay bale squeezes and stackers, but still be hauled by flatbed trucks and trailers on highways.	No bigger nor heavier than can be lifted and handled by skid-steer loaders and ground with small horizontal grinders at a central processing site. Fits with hauling on flatbed trucks and trailers on highways.
Bale density	Bale density needs to be adjustable depending on the storage and hauling scenario of any particular forest operation. Highest practical density (25+/- lb/cu.ft.) should be designed into the baler.	Bale density needs to be adjustable depending on the storage and hauling scenario of any particular forest operation. Highest practical density (25+/- lb/cu.ft.) should be designed into the baler.
Productivity	Maximize throughput that is limited only by ability of forestry tracked grapple loader to collect and feed materials into the baler. Make bales fast enough to keep up with the loader.	Ability to move rapidly between small piles and widely dispersed harvest landings is more important than total production rate.
Biomass pre-processing	Be able to accept materials up to 20 feet long with on-board slashing. Do not assume that grapple loader has slashing capability.	Be able to accept materials up to 20 feet long with on-board slashing.

On-site "system"	Assume that an operating unit is a large tracked grapple loader and one or two balers that operate in unison. Explore the potential to have the loader operator tele-operate the baler(s). Loader operator also clears and stacks completed bales, and loads outbound trucks. System may include two loaders and two balers, plus a fleet of haul trucks. The haul trucks/trailers are conventional flatbed type to reduce capital and maintenance costs.	Assume that an operating unit is a self-loading baler that includes a grapple and operator station. The baler may be track-mounted and moved on an equipment trailer pulled by a service truck or bale hauling truck. The system may include one or several all-wheel-drive self-loading bale hauling trucks that are decoupled from the baling operation by days or weeks.
Minutia (at least at this point)	Diesel fuel, strong safety features, spark arresters, durable, intuitive controls, …	Diesel fuel, strong safety features, spark arresters, durable, intuitive controls, …

Readers can now see that we are transitioning from the natural language objectives and constraints of stakeholders into the "natural language" of engineers and product managers. Each of the cells in the above table can now be discussed, debated, and restated as further-refined technical specifications.

Specification of Bale Size and Density

The above information and conceptual specifications were used to develop detailed specifications for bale sizes, density, and weights for forest residual balers of the two types. The design process and conclusions are documented in project report that is publicly available (J.H Dooley, 2015).

The bale design space is constrained by:

1. California highway transport regulations for trucks and tractor-trailers.
2. A loader with grapple is part of the baler system. The grapple loader will be used for bale handling within the forest and loading bales onto trucks. The loader and grapple may be either self-propelled or integral to the baler machine.
3. Bale handling and stacking at a centralized storage and processing site will be with conventional machinery as used in the hay and biomass industries or a skid-steer loader with gripping bucket. No new equipment should need to be invented for handling and processing the forest biomass bales.
4. Bales must be able to be fed into one or more current models of Peterson brand horizontal grinders without breaking the bale.
5. The baler itself will be designed around (constrained by) the preferred bale dimensions and bale density.

The truck and tractor-trailer constraint is "owned" by the trucking firms that deliver baled biomass on public highways. The current commercial semi-trailer size limits for California are 48-ft length (14.63 m) x 102-inches width (2.60 m) x 13.5 ft total height (4.11 m). If we allow for a trailer deck height of 4.5 ft, then the maximum payload height is 9-ft. Although the maximum legal payload height is 9-ft, we will target a maximum of 8-ft for our design purposes. This would allow for "straggler" sticks extending above the top surface of stacked bales. Although the current maximum payload width is 102-inches, a majority of the flatbed trailers in use in the western U.S. are 96-inches wide, which was the previous standard.

The payload weight limit for California is typically 44,000 – 48,000 lb (20,000 – 21,800 kg) for 48-ft long trailers depending on the specific truck/trailer configuration and trailer construction. Although weight limits are constraining to the total payload, if we bale to densities higher than about 15.6 lb/ft^3 (250 kg/m^3), the effect will be that fewer bales are carried per truckload and a portion of the deck will be unused.

The bale grinder infeed constraint is "owned" by the horizontal grinder company that is participating in the BRDI project. Their low horsepower grinders have an infeed height of 32 inches and an infeed width of 60 inches. Their high horsepower grinders have an infeed height of 40 inches or more and an infeed width of 60 inches or more.

We can now craft a table of plausible bale dimensions and projected bale weights for further consideration and selection. Selection of preferred bale dimensions, densities, and weights will then inform and constrain the next rounds of baler design. If bale properties become a major issue later in the design effort, the team can "back up" to the bale selection table to see if a more attractive bale size is available.

Table 3. Plausible set of bale dimensions when constrained by truck dimensional payload and Peterson grinder infeed. Preferred bale sizes are highlighted in yellow.

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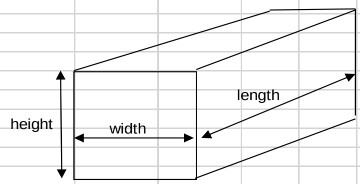
Candidate Forest Residual Bale Dimensions

Constraints
48-ft California semi-trailer (potential for 24-ft in-woods AWD flatbed truck)
fill 9x8x48 volume
stack in units or interweave
load with grapple
unload with grapple, fork lift, or bale squeeze



			Payload dimensions (in)					Bale Wt. (lb)			Truckload Payload (lb)			Truckload Payload(tons)		
		=48 or 96	108	96	576		Bale	Bale Density (lb/cu. Ft)			Bale Density (lb/cu. Ft)			Bale Density (lb/cu. Ft)		
height (in)	length (in)	width (in)	bales high	Bales wide	bales long	Bales/Trk	Vol (cu. Ft.)	30	23	15	30	23	15	30	23	15
30	40	48	3	2	14	84	33.3	1,000	767	500	84,000	64,400	42,000	42	32	21
30	48	96	3	1	12	36	80.0	2,400	1,840	1,200	86,400	66,240	43,200	43	33	22
32	44	48	3	2	13	78	39.1	1,173	900	587	91,520	70,165	45,760	46	35	23
32	48	48	3	2	12	72	42.7	1,280	981	640	92,160	70,656	46,080	46	35	23
32	**56**	**48**	**3**	**2**	**10**	**60**	**49.8**	**1,493**	**1,145**	**747**	**89,600**	**68,693**	**44,800**	**45**	**34**	**22**
32	64	48	3	2	9	54	56.9	1,707	1,308	853	92,160	70,656	46,080	46	35	23
32	72	48	3	2	8	48	64.0	1,920	1,472	960	92,160	70,656	46,080	46	35	23
32	82	48	3	2	7	42	72.9	2,187	1,676	1,093	91,840	70,411	45,920	46	35	23
32	82	96	3	1	7	21	145.8	4,373	3,353	2,187	91,840	70,411	45,920	46	35	23
34.4	96	47.2	3	2	6	36.61	90.2	2,706	2,075	1,353	99,072	75,955	49,536	50	38	25
34	**96**	**48**	**3**	**2**	**6**	**36**	**90.7**	**2,720**	**2,085**	**1,360**	**97,920**	**75,072**	**48,960**	**49**	**38**	**24**
36	72	48	3	2	8	48	72.0	2,160	1,656	1,080	103,680	79,488	51,840	52	40	26
36	82	96	3	1	7	21	164.0	4,920	3,772	2,460	103,320	79,212	51,660	52	40	26
36	96	48	3	2	6	36	96.0	2,880	2,208	1,440	103,680	79,488	51,840	52	40	26
40	48	48	2	2	12	48	53.3	1,600	1,227	800	76,800	58,880	38,400	38	29	19
40	56	48	2	2	10	40	62.2	1,867	1,431	933	74,667	57,244	37,333	37	29	19
40	84	48	2	2	6	24	93.3	2,800	2,147	1,400	67,200	51,520	33,600	34	26	17
40	96	48	2	2	6	24	106.7	3,200	2,453	1,600	76,800	58,880	38,400	38	29	19
48	84	48	2	2	6	24	112.0	3,360	2,576	1,680	80,640	61,824	40,320	40	31	20
48	96	48	2	2	6	24	128.0	3,840	2,944	1,920	92,160	70,656	46,080	46	35	23
96	96	96	1	1	6	6	512.0		11,776	7,680		70,656	46,080	-	35	23
96	192	96	1	1	3	3	1024.0		23,552	15,360		70,656	46,080	-	35	23

In earlier experiments, the Forest Concepts engineering prototype woody biomass baler produced bales up to 30 lb/ft^3 with green residuals, and up to 23 lb/ft^3 for field-dry residuals. We are including in the table a bale density of 15 lb/ft^3 which would result in a semi-trailer payload of approximately 20-23 tons, typical of allowable payloads on steel or aluminum trailers in California. The higher payloads may be allowable under situations where hauling is entirely on private forest road systems from the location of baling to centralized biomass processing sites. The design of the baler will have a capability to produce bales having a green bulk density of up to 30 lb/ft^3 with green residuals. Lower density can be attained by lowering the platen pressure when needed for a particular hauling scenario or to reduce the LCA fuel consumption of a baler.

We are also not constraining the bale dimensions and weight by potential limitations of biomass track-loaders using brush grapples. Gripping capabilities and lifting capacity constraints for loaders used across the forest operations sector are assumed to be sufficient for all bales being considered.

The bale dimensions in the table are arranged by bale height with selections to fit existing Peterson grinder infeed limits and to be stackable on flatbed trucks or trailers. Bale lengths are suggested with much more latitude since grinders do not have a length constraint. Bale width is generally set at either 48 or 96-inches to fully utilize the width of truck beds and to enable safe tie-down.

Bale length and width as used here are not necessarily associated with the direction that bale ties or strapping is placed. Neither is bale length necessarily the predominant alignment of branches and stems in a bale. The baler infeed may be 48-inches wide as is the case for the engineering prototype, or could be 84 or even 96-inches wide in a new forest residuals baler. The case for a wider baler infeed width includes lesser demands for biomass slashing and potentially fewer grapple loads to make a bale.

Slashing long branches and stems to fit into the baler can be accomplished ahead of baling during the sorting operation, with a slashing-type grapple loader, or on the baler itself. Since relatively few grapple loaders used in the forest industry have slashing saws, we are planning to include an on-board chainsaw-type cut-off saw or shear on the forest residuals baler (C. J. Lanning & Lanning, 2015).

Earlier work by Forest Concepts (Lanning 2007), and in the agricultural baler industry suggest that bales hold their shape better if they are more rectangular than square in the dimension the ties run. Thus, a bale that is 34-inches tall and 48-inches along the tie direction would be considered a better bale design than one that is 48x48.

The yellow highlighted rows in the table are preferred bale sizes under infeed constraints of various models of horizontal grinders and constrained by truckloads. However, at this point, the Forest Concepts team considers all of the bale sizes shown in the table to be producible.

At any bale size, the bale density is a function of the moisture of the raw biomass and the compaction pressure used to form the bale. As noted earlier, bale densities of approximately 15 lb/ft^3 will concurrently achieve both cube and weight limits for 48-ft highway trailers. Thus, we use that density as a lower constraint limit. However, even though they take more compressive energy to make, higher density bales take less space to store, hit payload with fewer bales to handle, enable very high payload hauling on forest roads, and may consume less bale tying material per ton. On the other hand, higher density bales will be slower to dry under natural air conditions.

Immediately evident from the table is the range of potential bale weights and truck payloads. At higher bale densities, full legal weight payloads are achievable with relatively “inefficient” volumetric payloads. Thus, a key point of discussion among the economic and LCA task teams needs to be the tradeoff of smaller, more easily handled bales, with the increased compaction energy needed to make high density bales. Later in the design effort, we will be develop an equation for baler fuel consumption (carbon emissions) as a function of bale density.

Rationale for the Two Bale Sizes Selected from the Table

We chose two bale sizes from the table of possibilities. A “small bale” was defined that can be ground by all current models of Peterson horizontal grinders, thus has a bale height of 32-inches and a bale length of less than 60-inches. The 48-inch bale width enables stacking two-wide on trucks and trailers. The recommended small-bale dimensions are 32-inches tall by 56-inches long by 48 inches wide. A “large bale” was defined to be similar to large rectangular agricultural hay bales which are nominally called 3x4x8 foot bales. The bale height dimension is somewhat smaller than three feet due to stacking limitations on highway-legal hay trucks. The recommended large-bale dimensions are 34-inches tall by 96-inches long by 48 inches wide. For clarification, the 96-inch dimension is produced across the baler platen, and the 48-inch width is in the compression dimension. The bales would be loaded on a truck with the 96-inch dimension along the truck bed in most cases. However, bales may be cross-stacked for hauling, handling with agricultural hay squeeze machines, or to create large bale stacks if needed.

The small bale is expected to contain approximately 750 pounds on a dry-weight basis and up to 1,500 pounds for green material at high density. The bale size is fairly close to that of the current Forest Concepts engineering prototype chipper-replacement baler, so the potential market for small-bale balers is an order of magnitude higher than for forestry balers. The larger market for small agile balers is likely to reduce the purchase cost of balers of this size by 30% or more compared to large special purpose forestry balers.

The large bale is approximately twice the volume of the small bale, and thus represents half the units to handle, load, and process compared to small bales. In a major shift from conventional balers, we propose to use a platen that is 96-inches wide and 34-inches tall that compacts along the 48-inch dimension. This scheme has the potential to create bales that could migrate toward round “bundles” during handling if insufficient branchy material is not randomly oriented within the bale. However, this “wide/short bale” has a number of benefits:

- Branches and tops need only be slashed to the 96-inch length, which is likely to improve feed rates.
- Compression along the 48-inch dimension greatly reduces the volume of hydraulic oil used by compression cylinders, which is likely to increase production rates.
- Compression along the 48-inch dimension is likely to substantially reduce “spring-back” forces that may enable use of lighter tie material and lower cost for ties per ton.
- Other implications may reduce the overall length of a baler which will improve mobility.

There are likely to be many common components between the two sizes of baler. For example, we may be able to use the same main platen hydraulic cylinders on both machines by installing two on the small baler and four or five across the large baler. Other similarities in how the bale compression produces Poisson’s forces will reduce engineering risk and design time.

Both balers will be top-loaded using the Forest Concepts patented infeed gate scheme (C. J. Lanning & Lanning, 2011, 2012) and use similar slashing saws on one end of the infeed for cutting over-length biomass (C. J. Lanning & Lanning, 2015). We expect that both balers will also fall within already-issued claims of Forest Concepts’ woody biomass baling patents (D. N. Lanning, Dooley, Lanning, & Fridley, 2011, 2014).

Summary and Conclusions

Development of high-level baler specifications and bale sizes was accomplished using the Appreciative Design Method to ensure that stakeholder and constraint-owner needs were considered. Specification of bale dimensions, configuration, and density are among the first decision decisions to be made for the design of a new class of forest biomass balers. The engineering team at Forest Concepts updated earlier work on baling of urban woody biomass to the context of forest residuals and the BRDI project. Revised functional objectives and operational constraints resulted in a new bale size specification that should be near-optimal for the BRDI project context.

Two bale sizes are specified for further development. The recommended small-bale dimensions are 32-inches tall by 56-inches long by 48 inches wide. The small bale will weigh between 750 and 1,500 pounds depending on biomass moisture content and platen pressure. The recommended large-bale dimensions are 34-inches tall by 96-inches long by 48 inches wide. The large bale will weigh between 1,500 and 3,000 pounds depending on biomass moisture content and platen pressure. These bale sizes will be used in the next stage of baler design which entails both overall baler configuration and concurrent specification of hydraulic power packages.

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