OPTIMIZING CONSTRUCTION EQUIPMENT FOR LONG-REACH EXCAVATION IN THE DREDGING INDUSTRY

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ABSTRACT

Dredging and marine construction contractors are able to select from a range of floating dredge designs and many types of standard land-based construction or earthmoving equipment from multiple manufacturers. At the interface of land and water, there are many work sites where neither is optimal and a custom solution is required. Marine construction projects in waterway restoration and protection require larger reach and lift capability while still meeting goals for productivity, operating cost, safety, environmental awareness and transportability. Solutions that combine these industry-specific requirements drive system level changes to truly optimize a machine for the task. There are a wide range of possible solutions to these goals separately, but combining them into an integrated package may require collaboration across organization boundaries to integrate hardware and technology. A customized solution requires a customized approach.

This paper will review a number of design and system changes made during the optimization of a long-reach 150 ton (330,000 lb.) excavator for a marine construction project and highlight some of the challenges involved. In the case study, a custom front attachment and counterweight solution was designed and integrated into the machine controls and also the tool guidance system. The customer application required collaboration between multiple organizations, highlighting how the diverse needs of the dredging industry requires a unique approach.

Keywords: machine modification, AEM, extended-reach, productivity, transport.

INTRODUCTION

A comparison of typical tasks for land-based earthmoving equipment versus dredging industry applications shows many similarities. Grading, removing or replacing material or operating hydraulic work tools such as grapples or hammers are common activities performed by tracked hydraulic excavators. The versatility and high user familiarity of hydraulic excavators have resulted in their common use on many construction sites, especially in the large size classes where many manufacturers offer products that can dig, load and perform special tasks that other machines cannot.

Industry trends of more challenging time goals and operational targets have continued to drive interest in large machines that can complete key functions in large marine construction projects with increasing productivity at lower operating cost. In many projects for shoreline protection for example, the scale and dimensions of graded earthworks and armor limit the use of standard land excavators that are designed for “mass-excavation” tasks such as trenching or mining. The contractor may have to decide whether to increase the size of the base machine or consider making modifications to overcome some of the base design features. In this paper, the authors will illustrate a number of typical considerations that must be made in the process of optimizing construction equipment and the complexity of this process versus purchasing larger machinery that may have increased capacity as standard.

Trailing suction or cutter head dredges can often be simply converted to operate at deeper depth with longer ladder options and a review of the slurry hydraulic transport conditions. The resulting equipment will still be constrained to certain material types, so heavy digging in hard or abrasive material or other tasks still drive the selection of mechanical dredging equipment such as a tracked hydraulic excavator.

The obvious difference that initiates most changes in excavators for dredging applications is the inability to locate the machine close to the task. The division between land and water may be sudden or gradual, but the challenges in bringing large equipment directly to the site are usually immutable. Many excavators can be driven onto floating pontoons to work directly above the task in shallow water without waves or swell, but there may still be safety concerns about stability of the platform during operation. Fixed or pedestal-mounted equipment is not considered in this paper due to the additional complexity of engine emissions legislation for permanently installed equipment in marine

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applications. Therefore, the most common result seen on many dredging and marine construction work sites is a front attachment with a long horizontal reach, depth, or a combination of both.

Requirements for the optimal operation of the longer front attachment must be carefully devised, including determining the digging and lifting forces required versus the reach and vertical distance from the machine. An application requiring maximum lifting at maximum reach has very different needs compared to digging hard and abrasive materials at depth, and there are pros and cons to consider for two-piece versus three-piece front designs. The additional stability demand of the longer and often heavier front may require a review of other aspects of the base excavator, including the counterweight and the undercarriage. This review must be based on an understanding of the constraints that apply to the base machine from the Original Equipment Manufacturer (OEM), and also the impact of changes on functional and regulatory aspects of the design.

Defining Excavation and Other Operational Requirements

The first step in the process to optimize a typical land-based excavator is to clearly define the specific digging, lifting and working envelope characteristics. Other factors such as targets for productivity (mass or volume of material moved or tasks per hour) and the overall capital budget must be defined to select suitable base machines that have the capacity to meet these requirements as standard or with some modification. Some requirements, such as meeting applicable environmental and safety regulations, are often common with the standard machine. Other requirements, such as needing the flexibility to be transported between jobs, and the overall owning and operating cost target, will be unique to the final configuration and they impact decisions made between standard or customized options.

Small hydraulic excavator models between 20 to 40 tons (44,000 – 88,000 lb.) will often include a range of stick and boom length options and offer undercarriage options of multiple track shoe widths and types for different conditions. The shorter reach options are typically advertised as “Mass Excavator” (ME) configurations with large buckets. The longer boom and stick options may be marketed as “General Purpose” (GP) or “Long-Reach” (LR) factory configurations and have smaller bucket and linkage sizes to maintain the manufacturer’s design for stability. The machine will usually offer additional hydraulic systems to power work tools such as hammers or grapples, and include connectors and pre-programmed controls to make switching tools a safe and efficient task. Some machines will have the option for additional counterweight available from the OEM where they are known to have heavy-duty applications on land such as forestry and material handling.

A key role of an OEM for standard equipment is to develop and provide literature describing the technical standards that apply to the base model. These will include regulation standards for sound performance, guarding against falling objects, rollover protection and safe lifting capacity. The development cost of meeting this burden of regulations may limit the range of options available for a given model. Consequently, large excavators, especially in the sizes above 100 tons (220,000 lb.), are typically not available with as many options as smaller models, and are often developed for mining and material removal applications with a focus on productivity in bench loading conditions. Although increasing the base machine size in terms of power and weight does increase most productivity characteristics, the capability for longer reach and lift does not typically scale in proportion. A typical 37,000 kg (81,571 lb.) excavator with 149 kW (199.8 hp.) of engine power will have a maximum horizontal reach of 10 m (32.8 ft.) for a ME configuration and 11 m (36 ft.) in GP configuration. These working ranges increase to 12.2 m (40 ft.) and 14.7 m (48.2 ft.) for similar ME and GP configurations for a 92,000 kg (202,800 lb.) machine with 405 kW (543 hp.) of power. However, a large excavator of 140,000 kg (308,650 lb.) weight may only offer a maximum reach of 14.1 m (46.2 ft.) with a ME configuration that is optimized for excavation work at close proximity. The user must match the critical characteristics of the desired end machine to a suitable base model to reduce the cost of modifications. The cost of the modifications can also be impacted by the support offered by the OEM in the modification process.

Identify A Project Partner

Having determined that the specific project need cannot be easily met with a standard machine from an OEM, the user must identify a partner to help with modifications. Many companies operate as an Auxiliary Equipment Manufacturer (AEM) and are active in providing services to design and manufacture special boom and stick assemblies or other excavator modifications. The choice of an AEM for larger machines and more complicated changes will be restricted to those able to work with larger fabrications and components or provide support in the regulatory type approvals required for the working region. A key example of this in Europe is the Machinery Directive 2006/42/EC that covers many requirements for risk assessments and protection against mechanical or other hazards that are part of the EC Declaration of Conformity. If the modified machine is to be sold, then it must be clearly identified who the manufacturer of record for the final machine assembly is. The required skills of the AEM must therefore include design and manufacturing engineering, meeting regulatory requirements as well as experience in sourcing customized components. They will be able to use this background to guide the various modification decisions to be made and provide advice on options to purchase from low-volume suppliers or make unique components.

The Design Process

The design of the modified machine typically starts with a two-dimensional concept of the working envelope to identify the length of the boom and stick. The AEM will work with the customer to identify the requirements for maximum rang, and the desired working conditions within this boundary. The working concept must include defining the hydraulic cylinder connection points and the boom angle to optimize the useful working range. Maximizing the stroke of the work tool avoids excessive movement, which can impact productivity, undercarriage wear and safety. Major decisions about using either a mono boom or a two-piece boom and how to mount the stick cylinder in relation to the boom are typically made at this stage after identifying the main function of the machine. A two-piece boom (also known as a Variable Angle boom) offers improved visibility and lifting capability close to a machine while retaining a long maximum reach, but will usually add a cost premium in components and system modifications. Moving the stick cylinder to locate beneath the boom can increase lift forces at maximum reach at the expense of maximum digging forces and requires only low complexity changes to the hydraulic control system. For Super Long Reach (SLR) machines, a quick coupling boom connection may be required if the front is excessively long when folded for transport or a secondary application requires a short boom for better digging force.

Most modified designs choose to replicate the standard geometry of triangulation between the boom, the lift cylinders and the standard pin spread of the OEM machine. More complex designs may modify the main frame of the machine to add larger diameter lift cylinders, or extra cylinders to increase boom lifting capacity, but it is generally not cost-effective to increase the hydraulic system pressure. The stick and bucket cylinders must be selected to provide adequate power and stroke length and, typically, smaller and lighter components are often selected in proportion as the length of the boom and stick increases. The concept design must be reviewed to verify the operating envelope does not cause interference as the stick and bucket pass through their maximum range of motion.

The concept for the front components is then transformed from two dimensions into three-dimensional components by calculating the cross-sectional area of the structures that will support the static and dynamic loads. These section properties are translated into material sheet selections for the main and interior supporting panels of the boom and stick. The design must review loading at the reinforced ends of the boom and stick, and transitions to general bending loads along each structure. The decision to modify or construct new fabrications depends on the level of modification and the availability of technical dimensional information about the standard components. This process can use either detailed measurements or computer-aided engineering to generate the detailed analysis of the assembly, but is generally easier where the OEM data is supplied to support the process. This phase may consider multiple options in the cost-benefit analysis comparing the price of heavier gauge materials and larger hydraulic components for the benefit they achieve. This design process ends with an assembly that includes the modified structures, and a combination of standard and alternative AEM components and a calculation of the component weight and center of gravity.

The next stage of the design concept is to analyze the tipping forces of the front attachment and payload, and determine if any additional counterweight or modified undercarriage is required. Lift capacity is differentiated from object handling capacity in some regions of the world, but is calculated by applying reserve factors to hydraulic power and tipping balance. Standards such as ISO 10567:2007 define rated lift capacity of a hydraulic excavator as the smaller of either the rated tipping load or the rated hydraulic lift capacity, but the real world must be considered before selecting a machine to operate at the rated capacity. The real world does not always comply with the assumptions made of flat, firm and level ground without strong winds or time pressures on operator training, fatigue or stress. The additional counterweight required to achieve stability may be between 25–200 % of the standard weight, so different solutions for mounting this to the machine may be adopted. Typical modifications take the form of an additional material sandwich or as bolt-on plates. The design must include whether the counterweight needs to be unloaded for transport and the equipment this may require. Demountable counterweight solutions reduce hazards of loading or unloading this weight on the job site or the cost of hiring other lift equipment.

Machine stability can also be increased by undercarriage modifications to increase the track length or track gauge depending on whether stability over the front or side of the machine is the prime objective. Modifications to the carbody or track frames of the base excavator can be challenging to design and implement due to the overall loads transferred through the machine. Variable gauge undercarriage enables the width to be reduced for transport, but increased at the workplace. Automated options to hydraulically actuate undercarriage changes or counterweight unloading increase the operational time on the job site and can reduce the potential for safety hazards due to operator error during assembly, but add cost in components and control systems to the modified machine. Cost of multiple loads or vehicles for transporting a partially disassembled machine between job sites must be compared with additional permits and insurance that may be incurred with moving the fully assembled machine for oversize or overweight loads.

There are many other potential modifications that can be made to optimize construction equipment, including customized guidance and controls, visibility and corrosion protection. All must be considered for the benefit they bring in comparison to the cost and difficulty to integrate into the base machine.

CASE STUDY: 29 M LONG-REACH EXCAVATOR

Following a case study for breakwater construction, a long-reach hydraulic excavator of at least 29 m (95.1 ft.) was identified as an early requirement for the project. The breakwater was designed for a port protection scheme using predominantly local material. The main tasks for the machine was to move and shape loads of rock into the profile of the core and add rock armor from an access road along the top. The size of the base machine and bucket size was directed by the volume of material to be moved in the project duration. STC B.V. from the Netherlands was selected as the AEM to design and supply the modified front attachment for the project, and a number of scenarios comparing different size machines were assessed for their performance against cost.

A concept for the working range was created based on a 150 ton (330,000 lb.) size excavator with a 15 m boom (49.2 ft.) and 12.4 m (40.7 ft.) stick using a bucket size of 3.0 m^3 (3.9 yd^3) from a smaller machine. The working range of this concept, shown in Figure 1, identified that a secondary requirement for digging at a depth of 22 m (72.1 ft.) could not be achieved, so a longer boom of 16.5 m (54.1 ft.) was designed. Alternative concepts for longer-reach targets of up to 36 m (118 ft.) were compared, but required an increase of the base machine size to around 200 tons (440,000 lb.).

A Cat® 6015B hydraulic shovel with a bucket capacity and payload of 8.1 m^3 (10.6 yd^3) and 15,000 kg (33,000 lb.), was selected to provide the hydraulic power for operating the long front. The mass excavation design of 7.6 m (24.9 ft.) boom and 3.4 m (11.1 ft.) stick has a maximum reach of 14 m (45.9 ft.), so the machine was purchased without the standard front for the new application.

A review of the hydraulic power requirements identified a number of changes to optimize the machine to the task. Larger diameter boom cylinders were selected and the standard stick cylinder was mounted in an underslung position to maximize lifting at the maximum envelope range. A smaller diameter bucket cylinder and linkage was specified to improve lifting capability by saving weight. The smaller components reduced the weight of the bucket, linkage and cylinder assembly by a total of 6,821 kg (15,038 lb.) as shown in Table 1. The final working range diagram is shown in Figure 3. The bucket linkage selection allowed a range of bucket sizes from 1 m^3 to 3.8 m^3 to maximize productivity when working with different sizes of rock armor.

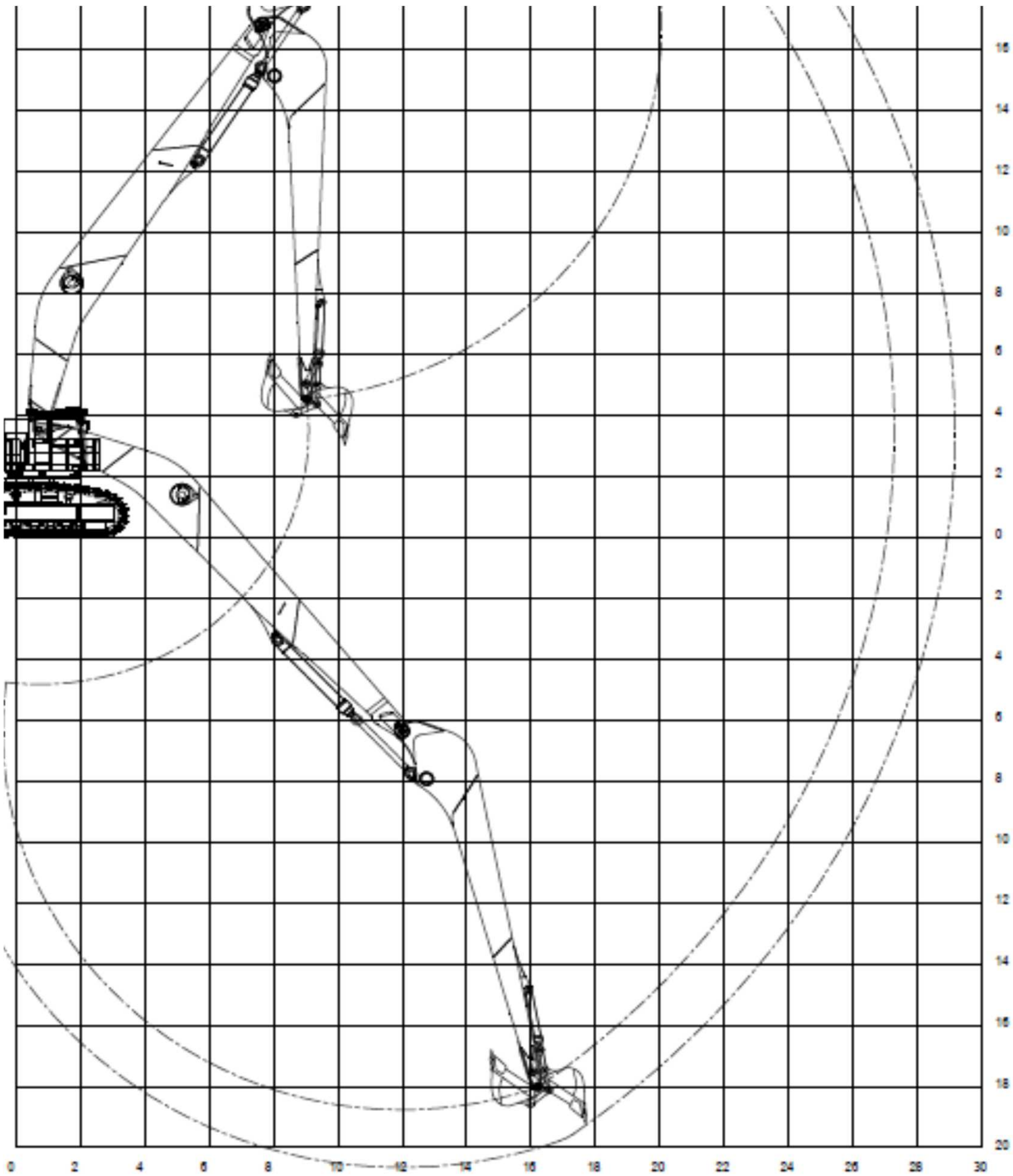

Figure 1. Concept of working range diagram for modified hydraulic excavator.

Table 1. Comparison of OEM bucket and linkage assembly component weights versus selections for customized long-reach excavator for dredging.

	Bucket	Linkage	Bucket cylinder	Total
Standard 6015B	7,528 kg	960 kg	1328 kg	9,816 kg
Custom design	2,373 kg	273 kg	349 kg	2,995 kg
Weight saved	5,155 kg	687 kg	979 kg	6,821 kg

Design of the mass and center of gravity of the boom and stick and selection of the lighter work tool components enabled a calculation of the tipping moment on the excavator (Figure 2). This identified that an additional 14,500 kg (31,967 lb.) of counterweight was required for stability. STC designed a sandwich of additional material to add to the standard counterweight, including extended supports to the frame. The large extra counterweight allowed the undercarriage to remain unchanged using the standard 700 mm (2.3 ft.) track shoe width. Ground pressure was a low priority in this application as the ground conditions were the access corridor along the breakwater, consisting of rock and gravel. The larger counterweight was designed to be manually unloaded for transport, but this was considered acceptable for a machine due to be working continuously on a single project for four years. This arrangement allowed the standard transportation layout for the machine to be used with the counterweight, track frames and front removed.

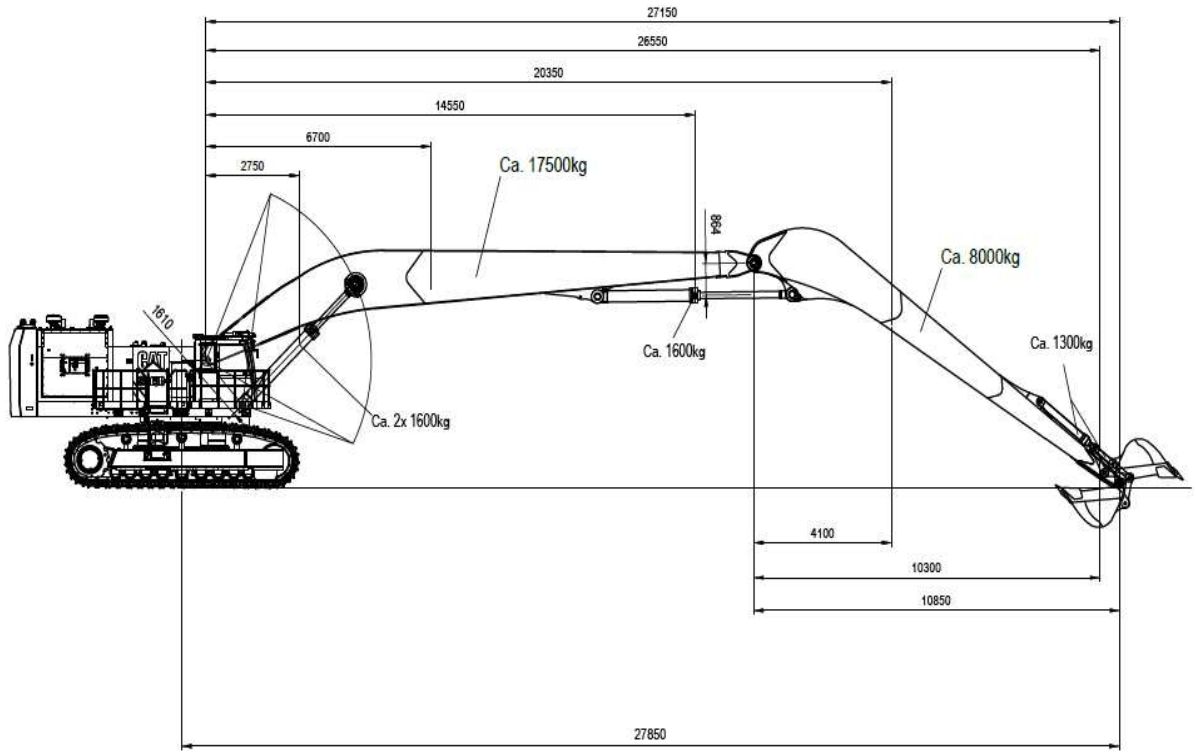

Figure 2. Tipping moment calculation information for customized front design.

Although the machine was to be working in an area that was easily accessible for maintenance support, serviceability and low downtime were important considerations in the design and thus impacted other specifications. The boom and stick were painted in a three-layer, 2K or two-component polyurethane paint system because of the application and time to be spent submerged in water. The base machine did not get any additional paint or coating because the work site was not typically subject to heavy surf conditions or spray.

A new greasing system for the front components was designed by STC to connect from the supply system of the base machine to the new locations of each moving part, and the service frequency was adjusted in the customer configuration of the machine. Marine specification grease was recommended with corrosion resistance and adhesion properties to resist water washout. The hydraulic cylinders and pins did not get any special modifications, but were set up as critical supply components in a monitoring and maintenance program. Along with regular inspections, the machine control systems were remotely monitored for error messages that would identify any upcoming need for service. An example of this type of configuration is shown in Table 2. Alternate options for marine grade hydraulic and greasing system components exist for these applications, but their use may offer better value in work sites that are less accessible and a long service life is required. In this project, the preferred approach was to use standard components that could be stocked as part of a preventative maintenance plan.

Table 2. Summary of Auto Lube and preventative maintenance setting options on customized machine.

Description	Value	Unit
Product ID	HSE00101	
Equipment ID	HSE00101	
Auto Lube Interval	10	min
Auto Lube Duration	180	sec
Access Ladder Installation Status	Not Installed	
Automatic Engine Speed Control (AESC) Delay Time	20.0	sec
Preventive Maintenance Enable Status	Enabled	
Preventive Maintenance Due Soon Warning Activation Time	50	hours

Detailed collaboration between the OEM and STC enabled the design to be executed and ready for a customer demonstration in five months. Dimensional information regarding the differences in the cylinder dimensions allowed the larger boom cylinders to be fitted to the frame. The modified stick cylinder application was integrated into the machine control system using an electrical conversion of the joystick output to reverse the standard action. The smaller bucket cylinder also required a modification to the standard system and a programmable controller was added to proportionally reduce the hydraulic flow. Although not pictured in the final design, options to add high pressure or medium pressure hydraulic functions were considered for using alternate work tools, but were rejected as the main tasks could be accomplished using only a range of buckets.

After completing all customer commissioning tests, the machine was disassembled for shipping and started work in September 2016. Photographs of the final machine at the work location are shown in Figure 4 and Figure 5.

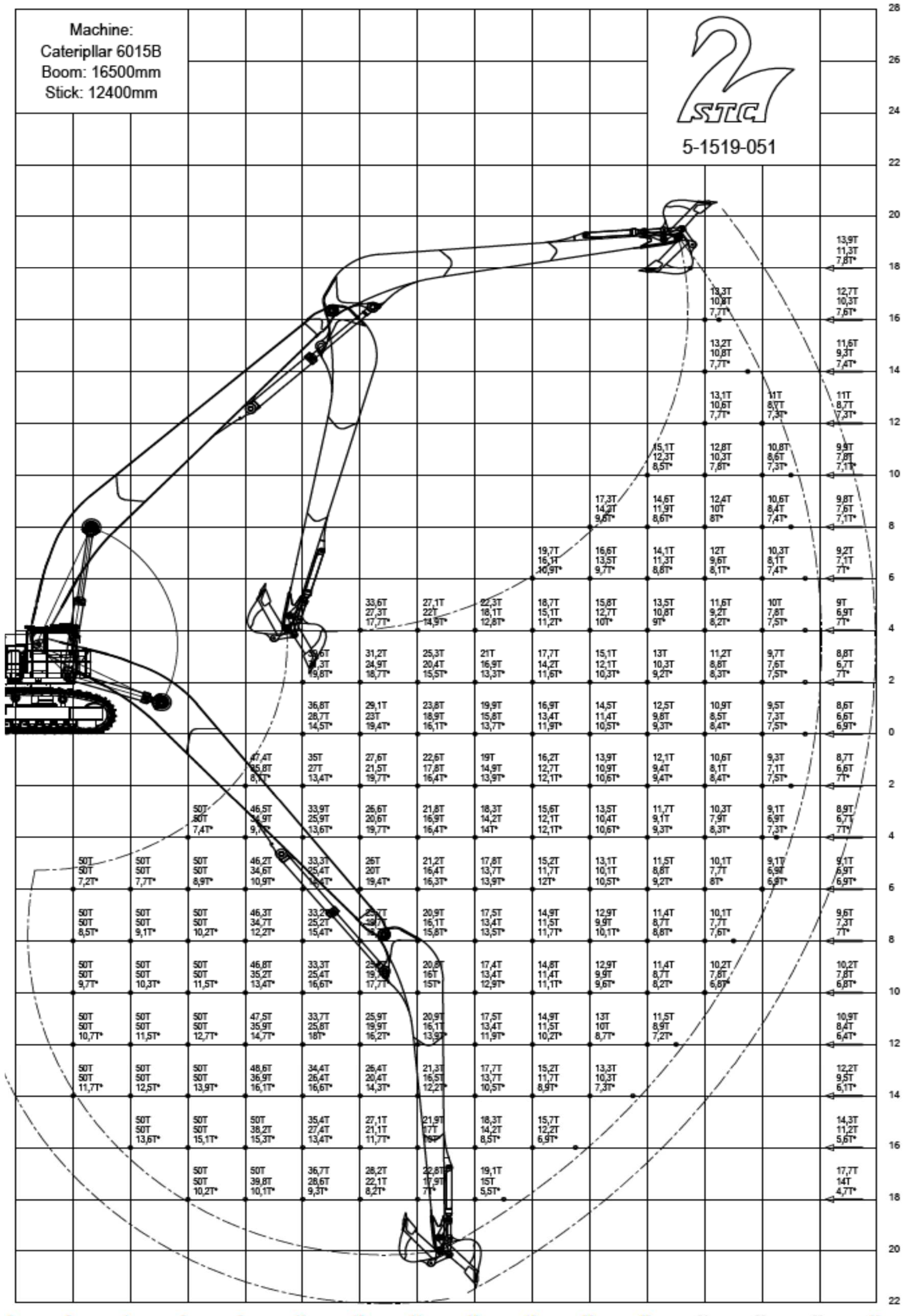

Figure 3. Final working range and lifting capability of customized long-reach excavator.

Figure 4. Customized 29 m (95 ft.) long-reach excavator at breakwater site.

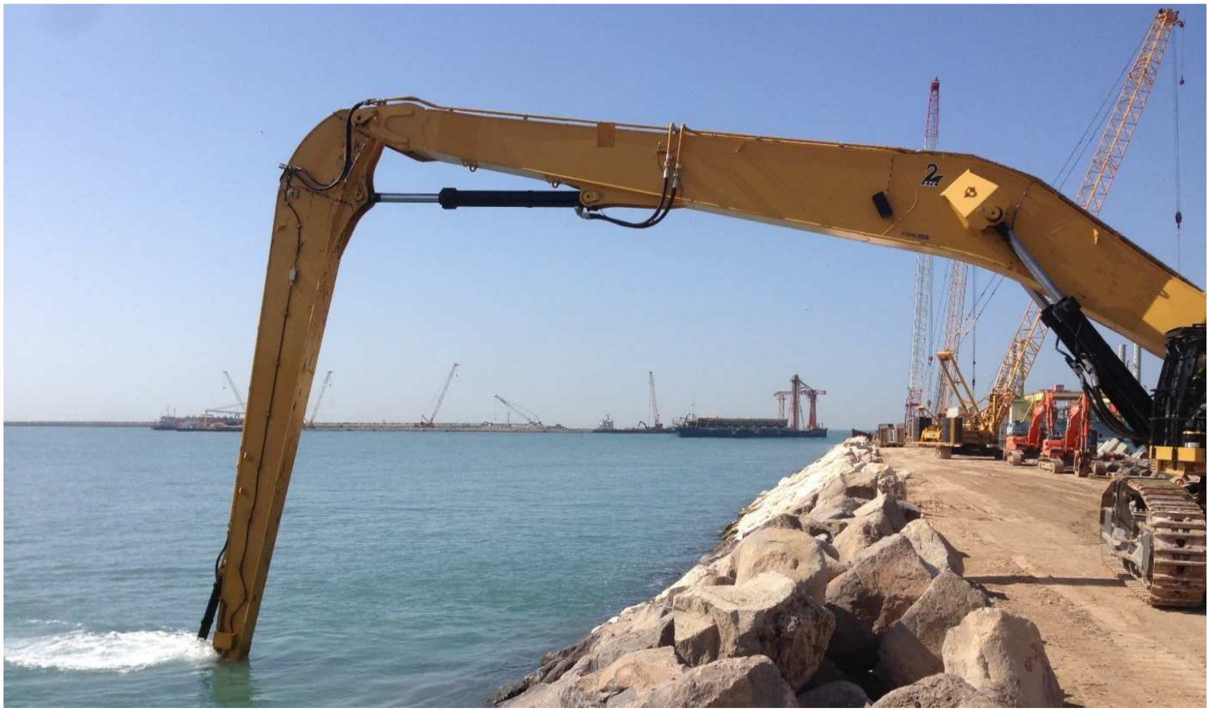

Figure 5. Customized 29 m (95 ft.) long-reach excavator at work in breakwater construction.

CONCLUSIONS

Although there are many standard excavator models available from a range of OEMs, there are frequently applications in the dredging industry where these do not meet the requirements. Many supporting businesses act as AEMs to help users modify and optimize standard machines for challenging tasks. The AEM can assist with the design process of determining how to achieve the requirements of a project, such as long-reach or depth etc., while meeting regulatory approvals with a solution that can be cost-effectively manufactured and transported. Serviceability and operating costs must also be considered in the cost-benefit review for all significant changes. The impact on long-term durability of the base machine from any modifications must be considered by the AEM and end customer as these will not be warranted by the OEM. The cost of successfully optimizing a machine will often depend on the level of support and engagement between the original OEM, the AEM and the user. The best advantage for the end customer is when the OEM and AEM can collaborate in support of the design process and the operation in the real world.

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