A systematic approach to the optimization of extra low profile (XLP) mine productivity for narrow reef platinum mines

M. ANDREWS and R.G.B. PICKERING
Sandvik Mining and Construction

Previous trials conducted by Anglo Platinum and Lonmin highlighted the importance of the series nature of XLP mining and the impact of addressing bottleneck constraints on overall mine productivity and output. Prior trials completed at Anglo Platinum Bathopele Mine and Lonmin identified the performance of the XLP roof bolter as the primary system bottleneck. Sandvik Mining and Construction undertook to evaluate current XLP system performance, quantify individual machine performances and address bottleneck constraints, applying Goldratt’s Theory of Constraints. The roof bolter was indeed found to be the primary system bottleneck and this paper initially attempts to define the measures undertaken to improve XLP bolter performance and quantify the impact of addressing the bottleneck on overall mine productivity. Once XLP bolter improvements were implemented, it was seen that the bottleneck had shifted to the LHD performance within the cycle. By optimizing the loading and hauling activity, improvements were experienced, however, their effect was less pronounced than the XLP roof bolter initiative, implying that additional system constraints existed. Further studies and analyses highlighted panel availability as the next primary system factor, directly influencing overall mine output. A revised section layout and configuration is therefore proposed which, if tested and implemented, could lead to an additional 32% increase in system output. This paper therefore attempts to describe the measures undertaken to eliminate a combination of machine and application bottleneck constraints in current XLP mining system and highlights the importance of applying a systems approach to XLP mine optimization.

The need to simultaneously mechanize and optimize operations

Industrialization and automation within a range of industries, together with a shift in demand for labour towards service-related industries, means that personnel who are willing to work within confined underground...
environments are often limited. Add a cumbersome jackleg to the mix and people are even less inclined to perform underground, which means that demand and subsequent costs within the conventional mining industry have escalated substantially. The increase in HIV/AIDS within developing countries exacerbates this problem further. The introduction of mechanized mining methods often alleviates the above problems by:

- Reducing the physicality associated with mine activities.
- Improving the environment in which personnel operate (air-conditioned cabins for example)
- Substantially reducing the risk of injury and harm to personnel by removing them from the working face and mechanizing a number of the activities
- Reducing labour requirements although personnel working in mechanized environments often have to have additional and scarcer skill sets to operate the equipment correctly.

Although the above are imperative prerequisites for any socially conscious company, it would make no sense to go into business unless the above could be achieved economically and optimally. The substantial reduction in PGM prices, attributed primarily to the decline in the platinum price, as depicted in Figure 2, has forced mining companies to focus on efficiencies and effectiveness within their operations.

The shift from standard profiles to low profile mining and to extra low profile mining is one means of optimizing the extraction of PGMs due to a substantial reduction in stoping width; this significantly reduces dilution, thereby minimizing costs associated with handling and processing of waste material. This is emphasized in Figure 3, comparing XLP mining net operating profit after tax (NOPAT) to standard low profile and conventional mining NOPAT respectively. Figure 3 clearly shows that the NOPAT associated with XLP mining is far higher than standard LP mechanized mining methods and conventional mining methods respectively over the life of mine duration.
The series nature of XLP mining

The series nature of XLP mining within the current mine configuration implies that each panel needs to have some activity being performed at any given time. This is illustrated in Figure 4.

Figure 4 shows that:

- One panel needs to be drilled with the XLP drill rig, and charged for blasting.
- The preceding panel needs to be cleaned using the XLP dozer and the LHD.
- The panel above should be supported with roof bolts using the XLP roof bolter.
- Secondary support needs to be installed at predefined blast intervals using either wooden props or grout packs. Although this can, at times, be performed simultaneously with the activities above, it is recommended that a fourth panel is made available, particularly if grout packs are installed.
- Ideally one additional panel needs to be available as a buffer to the system in case the cycle does not take place according to plan. It also allows development to occur simultaneously within the advanced strike drives (ASDs) while simultaneously stoping the panels.

The cycle above provides a typical example of a system in series and implies that any manageable system is limited in achieving more of its goal by a very small number of constraints, and that there is always at least one constraint as depicted in Figure 5.

According to Goldratt, five focusing steps should be adopted to address such a system, defined as:

1. Identify the constraint (the resource or policy that prevents the organization from obtaining more of the goal).
2. Decide how to exploit the constraint (make sure the constraint’s time is not wasted doing things that it should not do).
3. Subordinate all other processes to above decision (align the whole system or organization to support the decision made above).
4. Elevate the constraint (if required or possible, permanently increase capacity of the constraint; ‘buy more’).
5. If, as a result of these steps, the constraint has moved, return to Step 1.

The above methodology was adopted for the XLP mining system in an attempt to optimize the efficiency of the XLP cycle as described below.

XLP activity bottleneck identification

A detailed time-and-motion study was conducted at Anglo Platinum’s Bathopele Mine by Sandvik Mining and Construction’s trans4mine™ department—a team which has been assembled as part of Sandvik’s Business Development offering to assist mines in optimizing current operations from a systems and applications’ perspective.

Results of the time-and-motion study, conducted over a two-month period, are shown in Figure 6. Note that Bathopele Mine operates three by eight hour shifts and it is assumed (for this study) that five of the eight hours is effectively available for productive operation of XLP equipment (indicated by the red line in Figure 6).

The results clearly show that the XLP roof bolter is the obvious activity bottleneck within the XLP cycle and, according to Goldratt’s theory of constraints, should be addressed first if we expect any improvement in overall XLP system performance.

In order to understand the XLP bolter constraint further, each task within the XLP bolting process was measured and is illustrated in Figure 7.

Issues and identified solutions associated with optimizing each of the tasks above were analysed and are summarized below:

- The rod coupling procedure is cumbersome and time-consuming, contributing 21% additional time to that associated with a standard non-coupled bolt. Time is required to couple and screw the threaded R23 rods together, prior to relocating the drill string on the drifter and raising the feed back into the hole. This is a manual
process, thereby compromising operator/assistant safety (the assistant runs the risk of injury when coupling the bolt and is in the vicinity of potential rockfalls during the process).

- The need to use four rods in order to attain the 1.6m bolt hole length poses the same safety and time constraints as those discussed above with the coupling process. Any possibility to reduce coupling requirements would substantially improve cycle time and reduce the potential of personnel injury/harm.
- Due to the nature of the tramming system, positioning of the machine directly over the target where the bolt is supposed to be installed is difficult to achieve; tramming currently lacks proportionality, which makes machine movement relatively ‘jerky’ and difficult to carry out to the required levels of accuracy.
- The bolt installation process is completely dependent on the XLP roof bolter due to the added requirement of inserting, spinning, and securing the bolt; the forces required with resin bolts requires mechanical assistance to perform these functions. The injection and installation process therefore reduces the machines capacity to drill by 36%.

### XLP bottleneck optimization

In order to address the above constraints associated with the XLP roof bolter activities, the following initiatives were implemented:

#### Drilling optimization

A new XLP roof bolter feed was designed with a longer stroke ensuring that three rods could achieve the desired 1.6m hole length instead of the four rods which were previously required (refer to Figure 8).

The revised design resulted in a reduction in drilling time of 27 seconds per bolt (19%) and a 6% improvement in overall bolt cycle time. Incidentally, the feed was also modified from a chain feed to a rope-cylinder feed which, to date, has yielded a 50% improvement in reliability.

#### Bolt installation optimization:

A decision was taken to attempt to ‘de-couple’ the drilling of the bolt hole from the installation of the bolt. After considering several possibilities, the selected solution was to test New Concept Mining’s Hydrabolt™, a type of friction bolt which encapsulates water (shown in Figure 9). The bolt is manually installed using a separate water pump and can be carried out after the XLP roof bolter has completed drilling the hole, allowing the XLP machine to proceed to the next hole and start drilling while the previous hole’s bolt is installed. Although the implementation the Hydrabolt™ does not necessarily optimize the number of personnel at the workface, it is viewed as an interim solution, whilst a mechanized solution is being developed.

Implementation of the above resulted in a reduction in overall XLP roof bolter cycle time of 156 seconds per bolt (35% improvement in bolt cycle time).

#### Rod coupling optimisation

In order to reduce coupling time associated with the extension drilling process, a newly designed drill rod and couplings were developed termed the Infinity™ range (shown in Figure 10). The Infinity™ drill steels were named such due to their figure-eight coupling shape which was relatively easy to manufacture and far easier to couple during the drilling process of the bolt hole. The introduction of this steel resulted in a 61-second improvement in overall cycle time per bolt, representing an overall improvement of 13% to the bolt cycle time.

#### Machine/boom movement optimization

In order to accurately and efficiently position the machine under the required hole, proportional tramming was developed allowing for precise location of the machine over
the bolt hole with minimal effort. This is currently being tested at Anglo Platinum Bathopele Mine. However, provisional results to date show an overall improvement of 10 seconds per bolt (2% improvement in overall cycle time).

The above initiatives are summarized in Figure 11, highlighting the improvement in each activity relative to the previous XLP roof bolter configuration:

Applying the above to all activities within the XLP cycle, it can be seen that the XLP roof bolter has shifted from the bottleneck activity to the best performing activity within the cycle (Figure 12). The optimization improvements stated above should also yield a 30% improvement in overall fleet productivity attributed to these improvements.

According to Goldratts’ theory of constraints, the next activity that needed to be addressed was the LHD machine as this had shifted to the new bottleneck activity. This was relatively easily remedied as Sandvik Mining and Construction had just recently tested and implemented a new 8 tonne LHD (6.4 tonnes with ejector bucket as required by XLP mine layouts) as shown in Figure 13.

The above prototype was run as a trial at Anglo Platinum Bathopele Mine and yielded an improvement from 3.9 tonnes/bucket to 5.2 tonnes/bucket (median values) while maintaining the same number of loads as the smaller EJC 115 LHDs. This resulted in an overall loading cycle improvement of 33%. It is important to note that the mine is considering using only one LH208L in place of the two smaller EJC 115 LHDs, implying that the defined 33% improvement will not be realized; however, mine capital and operating cost outlays for LHDs will essentially be halved. Assuming for consistency purposes that two LH208L LHDs are used (as per the previous system definition), the overall system improvement is illustrated in Figure 14.
The above machine fleet improvements can be summarized in terms of expected blasts per day and expected square metres achieved on a daily basis as defined by Table I.

Although substantial improvements were initially achieved with the optimization of the XLP roof bolter, it can be seen that incremental improvements thereafter were seen with the introduction of the larger LHD; the reason for the small improvement in overall system performance is due to the XLP face rig almost immediately becoming the new bottleneck with a small improvement in LHD performance despite the substantial overall performance improvement with the introduction of the larger LH208L LHD. This is expected to occur due to the fact that the range between the bottleneck machine and the best performing machine is beginning to converge. It is also obvious from Figure 14 that although all machines are capable of comfortably achieving their shift targets within the predefined effective shift time other system constraints outside of machine capabilities alone may be hampering system output, implying that machine performance alone may not be the ultimate system bottleneck.

Mine configuration and layout optimisation

The above results demonstrate the application of Goldratt’s TOC model while focusing on the XLP machine fleet alone. One limitation with the above method is that it assumes infinite system capacity in terms of panel availability. The unpredictable nature of underground mining means that production is often lost due to panels being ‘lost’ as a result of poor ground conditions such as faults, dykes, and potholes. This is closely related to the current mine and section configuration which is briefly summarized below, together with identified constraints. A revised mine and section layout is then proposed intended to address some of the key constraints associated with the layout.

Current mine and section configuration

Anglo Platinum has defined a comprehensive set of mine design criteria (MDC) which provide guidelines for XLP mining for dip angles of 10º and below. In general, the overall XLP layout consists of 4 strike sections, separated by a five-set decline as indicated in Figure 15. It is intended that three of the four strike sections are in production at any given time with the fourth strike section being upgraded and advanced with activities such as service installations, belt extensions and borehole radar drilling.

Each strike section consists of nine panels (36 metres in length, skin-to-skin) with two suites of equipment operating within each strike section. An additional ‘swing suite’ of equipment is provided to ensure that production continues while machines are being serviced. A comprehensive conveyor system is located at the centre of the strike section with an extensive set of dip belts and fish belts to reduce LHD tramming distances and a satellite workshop is available for machine services. A schematic of each section is provided in Figure 16.

Table I

<table>
<thead>
<tr>
<th></th>
<th>Base case</th>
<th>Roof bolter optimization</th>
<th>Roof bolter and LHD optimisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Available hours/day (h)</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Bottleneck activity</td>
<td>XLP roof bolter</td>
<td>LHD</td>
<td>XLP face rig</td>
</tr>
<tr>
<td>Bottleneck duration (h)</td>
<td>5.6</td>
<td>4.3</td>
<td>4.2</td>
</tr>
<tr>
<td>Achievable blasts/day</td>
<td>2.67</td>
<td>3.49</td>
<td>3.57</td>
</tr>
<tr>
<td>m² per blast</td>
<td>50.16</td>
<td>50.16</td>
<td>50.16</td>
</tr>
<tr>
<td>Achievable m²/day</td>
<td>134</td>
<td>195</td>
<td>199</td>
</tr>
<tr>
<td>% improvement</td>
<td>-</td>
<td>31%</td>
<td>34%</td>
</tr>
</tbody>
</table>

Figure 15. XLP macro-layout1

System constraints

Major system constraints associated with the MDC layout are summarized below:

- The need to develop a 9-panel section prior to production commencing requires substantial development to occur within the strike section which incurs significant time and represents an opportunity cost.
- A substantial amount of decline development is necessary to reach the bottom of the four strike sections, which again increases the ramp-up period to full production.
- Lack of predevelopment and use of borehole radar implies limited orebody knowledge, resulting in fewer operational panels due to geo-losses.
- Re-raising beyond potholes is expensive and time-consuming.
- The conveyor configurations are expensive and time-consuming to move.
- The above introduces the need for an additional strike section to be available for preparation and establishment. This is expensive and has no immediate returns in terms of revenue.

The above constraints all contribute to a decrease in the possibility of optimizing panel availability. A summary of potential panels available versus panels lost per section is summarized in Table II for two of Anglo Platinum Bathopele Mine’s XLP sections from August 2009 to April 2010. Note that panels were lost for a range of reasons and may have not have been available for only a period within the defined month.

Figure 15. XLP macro-layout1
It is interesting to note the following observations from Table II:

1. On average 32% of all potential panels were not consistently available to be stoped over a 9 month period; this represents an average of approximately 2 'unproductive' panels per section at any given time within each section per month.

2. Based on Figure 4, it can be seen that a minimum of 4 panels per section is required to optimally carry out XLP mining; shaded examples in Table II show those months where fewer than 4 panels were continually available for stoping, implying that the XLP cycle could not be optimally implemented (1 out of 9 months for Section A versus 5 out of 9 months for Section B).

3. The positive impact of having an additional panel within an XLP section (Section A with 6 potentially available panels versus Section B with 5 potentially available panels) can clearly be seen when observing the number of occurrences where XLP cycles cannot be effectively implemented (shaded examples). On average a six-panel section can be effectively stoped 89% of the time (8 out of 9 months) whereas a five-panel section can only achieve an optimal cycle 44% of the time (4 out of 9 months). This will more than likely be case specific for different sections. However, it does highlight the relationship between section size, panel availability, and the ability to continually achieve the XLP cycle.

The wish list

In order to address the following constraints, and panel availability in particular, the following wish list was defined:

1. Provide a similarly sized section to the MDC solution with reduced development requirements (metres and cost) and an equal (or greater) number of panels per section.

<table>
<thead>
<tr>
<th>Month</th>
<th>Section A</th>
<th></th>
<th>Section B</th>
<th></th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total panels</td>
<td>Panels lost</td>
<td>Total panels</td>
<td>Panels lost</td>
<td>Total panels</td>
</tr>
<tr>
<td>Aug-09</td>
<td>6</td>
<td>3</td>
<td>5</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>Sep-09</td>
<td>6</td>
<td>2</td>
<td>5</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>Oct-09</td>
<td>6</td>
<td>2</td>
<td>5</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>Nov-09</td>
<td>6</td>
<td>2</td>
<td>5</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>Dec-09</td>
<td>6</td>
<td>2</td>
<td>5</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>Jan-10</td>
<td>6</td>
<td>0</td>
<td>5</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>Feb-10</td>
<td>6</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>Mar-10</td>
<td>6</td>
<td>1</td>
<td>5</td>
<td>3</td>
<td>11</td>
</tr>
<tr>
<td>Apr-10</td>
<td>6</td>
<td>2</td>
<td>5</td>
<td>3</td>
<td>11</td>
</tr>
</tbody>
</table>

Total average 32%
• Reduce panel establishment time to increase net present value (NPV) and internal rate of return (IRR) results.
• Promote extended orebody knowledge prior to mining (predevelopment) to promote reliable section designs and subsequently optimise mine planning.
• Ensure all sections which have been developed are producing at any given time.
• Limit panel loss (or its effects) due to geotechnical constraints.
• Provide a conveyor system which is easy to extend and does not impact the mining operation during transfers.

The proposed solution
In order to achieve the above wish list and eliminate the defined constraints, a revised mine layout was developed with equal or improved criteria as opposed to the MDC parameters. Summary illustrations of the refined strike section and mine layout are shown below and discussed in further detail:

• It is proposed that each strike section is adapted comprising four panels with skin-to-skin panel lengths of 36.4 m as per the MDC specifications.
• Each strike section would be predeveloped, two raise lines ahead, to ensure that ventilation is optimized and that no vent columns are located near to production blasting. Predevelopment will also increase orebody knowledge allowing for optimized planning and scheduling to occur.
• By predeveloping two raise lines ahead of stoping, panels can be stoped from both sides, thereby converting a typical four panel strike section into an eight-panel equivalent section.
• A conveyor would be located at the top and bottom of each strike section with allocated locations for stoping and development respectively. This will reduce tramming distances for LHDs and allow belt upgrades to occur independently.

In order to ensure that production output from the mine equals or improves on the existing MDC model, it was decided that the number of panels should equal or exceed the MDC criteria from a macro-scale. It is therefore suggested that 3 sets of the strike sections defined in Figure 17 are combined to form the overall production layout as illustrated in Figure 18.
It is suggested that a single dedicated suite of equipment is allocated to each strike section with an additional ‘swing suite’ to be shared between pairs of strike sections as summarized and compared in Table III.

The suite complement comparison above emphasises the fact that the revised Mine design has exactly the same fleet size as the MDC model implying that the revised mine design will not compromise capital and operating costs associated with equipment.

A comparison of MDC system parameters and proposed Predevelopment design parameters are listed in Table IV.

**Revised system benefits**

Benefits of the revised system are summarized as follows:

- Each suite of equipment can operate within an eight-panel layout: Even with panel losses of 32% as calculated above, this amounts to a minimum of 5 panels per suite, which is ideal for XLPM machine and process cycling.
- Once the macro-section has been developed, each strike section is continually in production ensuring that revenue is maximized in terms of NPV and IRR.
- The inclusion of 4 dedicated and defined tipping points for production and development ensures that tramming distances are always maintained below 120 metres (one way).
- The belt configuration allows for belt upgrades to take place without interrupting production.
- Predevelopment greatly improves orebody knowledge and subsequent production planning, potentially improving production by 25% plus.
- The stoping and development activities take place independently in separate sections within each strike section, ensuring that interference does not occur between these functions.

### Table III

<table>
<thead>
<tr>
<th>Machine suite requirements - MDC vs proposed</th>
<th>MDC design</th>
<th>Pre-developed design</th>
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</thead>
<tbody>
<tr>
<td>Number of strike sections</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Number of strike sections in production</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Number of dedicated suites/strike section</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Number of swing suites/strike section</td>
<td>1</td>
<td>0.5</td>
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<tr>
<td>Total number of suites of equipment</td>
<td>9</td>
<td>9</td>
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### Table IV

<table>
<thead>
<tr>
<th>System parameters MDC vs. Pre-developed design</th>
<th>MDC design</th>
<th>Revised design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of strike sections</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Number of strike sections in production</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Panels per strike section (100% available)</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>Panels per strike section (35% geo loss)</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Panels per suite of equipment (100% available)</td>
<td>4.5</td>
<td>8</td>
</tr>
<tr>
<td>Panels per suite of equipment (35% geo loss)</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Total panels in production per macro-layout (100% available)</td>
<td>27</td>
<td>48</td>
</tr>
<tr>
<td>Decline development metres for macro-layout (m)</td>
<td>668</td>
<td>501</td>
</tr>
</tbody>
</table>

- Less decline development metres are required, however, more strike and raise development will be necessary to predevelop each section.
- Longer section length along the strike direction (90 m versus 45–60 m) implies less raise line development, which leads to a lower overall development ratio.

**Revised system constraints**

The primary argument with the revised model is the additional development (strike and raise) necessary to predevelop the section as opposed to stoping and developing simultaneously within the same panel region. It is estimated that the MDC ramp-up to steady state takes approximately 17 months whereas the predevelopment model will take approximately 23.5 months to full production. It is, however, felt that the impact on NPV and IRR attributed to the longer lead time to full production would be far outweighed by the proposed improvement in production output attributed to the machine cycle and panel availability improvements stated above. Several alternatives do, however, exist to improve this ramp-up period stated above which will ultimately improve NPV and IRR results:

- Predevelopment could take place to the point of one raise line ahead (as opposed to two raise lines as originally proposed). This would reduce the ramp-up period by approximately 6 months, aligning targets with the MDC model. It would, however, complicate the ventilation requirements.
- The inclusion of an additional two development rigs, shared amongst all six strike sections, will reduce ramp-up time by 6 months. Introducing the LH208L in place of two EJC 115 LHDs, may justify the inclusion of two additional rigs while maintaining predevelopment two raise lines ahead of stoping.

The base case predevelopment model therefore needs to be tested further using an NPV and IRR model and if identified to be uneconomical, then the above two alternatives could be reassessed further.

**Conclusions**

The above analysis highlights the importance of considering mine system constraints when attempting to optimize mechanised machine solutions. A substantial expense can be incurred by focusing on perceived constraints which may not ultimately form the overall system bottleneck. It is therefore essential to assess each mine as a system, step through the processes involved utilizing a process mapping approach, and apply a methodology similar to Goldratt’s theory of constraints in order to optimize a particular operation. The initiatives highlighted above attempt to optimize machine cycles by analysing the activities associated within the cycle as well as the environment in which the machinery operates. Although several of the machine cycle constraints have been addressed, additional effort is still required to fully justify the proposed mine solution to ensure that it suitably addresses safety, operational and economic constraints. It is felt that the incorporation of such a layout will, however, ultimately alleviate the next hurdle/bottleneck related to panel availability, thereby shifting the bottleneck and providing the opportunity for further optimization to take place.

**References**


Michael Andrews

*Trans4mine Project Manager, Sandvik Mining and Construction.*

I have worked for Sandvik Mining and Construction for 6 years during which time I worked as a Technical Project Manager, an Account Manager and a Sandvik trans4mine Systems Engineer and trans4mine Project Manager. I formed part of the team responsible for developing and implementing the Sandvik trans4mine department and offering, a global consulting department assisting mines in optimising productivity and reducing operational costs. I have run trans4mine projects locally in South Africa, in Africa (Zambia), and in Europe (Bulgaria).